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Functional Modeling through Energy Flow Diagrams for Novice Engineering Design Students

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Functional Modeling through Energy Flow Diagrams for Novice Engineering Design Students

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Dedication

This thesis is dedicated my family, my teachers and my friends. All of whom are responsible for who I am today.

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Dr. Richard Crawford and his journey of who he is today is an inspiration for many. I am one of them. His drive to make a difference in engineering education is contagious. I consider myself lucky to have worked with him in the past few years. I learned more than engineering from him. I learned humility and passion from him which are what I consider his most valuable teaching to me.

I would like to thank Dr. Maura Borrego for her guidance and for answering my questions patiently throughout the progress of my research. Her will and determination are things that I strive to emulate.

Functional Modeling through Energy Flow Diagrams for Novice Engineering Design Students

By

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The University of Texas at Austin, 2015

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The UTeach*Engineering* program from The University of Texas at Austin is currently developing a high school engineering curriculum that emphasizes design, project-based learning, and development of engineering habits of mind. One module in the curriculum uses reverse engineering of an electromechanical device to teach functional modeling, among other design methods and techniques. Experienced engineers think in terms of the functions – what a product or system must do – before they determine what it will be in its physical form. This is an abstract way of thinking that is commonly taught to engineering undergraduate students, but can be difficult for high school students to grasp. To assist novice engineers (both high school students and undergraduates), a new approach has been developed and evaluated. The Energy Flow Diagram (EFD) focuses on modeling and documenting the energy flow and transformations in the product or system. Energy conversions are prevalent in most products that are feasible for high school students to reverse engineer, and we hypothesize that the results of energy conversions are evident in the behavior of these products. In this paper, we describe the EFD and the materials developed to support its teaching. The EFD method was piloted with an assortment of students from different majors and year of study in the undergraduate level. A pre/post-test was conducted to evaluate any increase in functional thinking among novice design engineers. It was found that the tool was much simpler to understand and implement, and also provided some insights for product redesign opportunities that are similar to the current method of teaching functional modeling.

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INTRODUCTION AND PROBLEM BACKGROUND

1.1. INTRODUCTION

Engineering is a Science, Technology, Engineering and Mathematics (STEM) field where different areas of science become relevant to each other and integrate seamlessly to produce tangible results. According to the US Department of Commerce, the need for STEM jobs will grow by 17% by the year 2018 and there will be 1.2 million jobs that cannot be fulfilled at the current graduation rate of STEM majors (Langdon, McKittrick, Beede, Khan, & Doms, 2011). To prepare for such a scenario, it is important that the next generation is educated in the STEM field. This is vital for the future sustainability and growth of the country. In order to solve this problem, it is important that the nation influences children from a very young age to pursue STEM education and careers. To create a passion among the next generation about engineering, a number of programs were developed in the US to enhance K-12 STEM education.

1.1.1. UTEACH

UTeach is a training program for aspiring secondary and the in-service teachers in STEM education developed at the University of Texas at Austin in the year 1997. It is a collaborative effort by the school of natural sciences and the school of education. In 2008, UTeach*Engineering* was started as a collaborative effort between the College of Natural Sciences, the Cockrell School of Engineering, and the College of Education at The University of Texas at Austin and the Austin Independent School District. The main mission of the program is to improve public education providing support for engineering education in high schools.

1.1.2. *ENGINEER YOUR WORLD* CURRICULUM

Engineer Your World (*EYW*) is the engineering design curriculum developed by The University of Texas at Austin faculty in collaboration with NASA engineers to teach high school students engineering practices. The curriculum is essentially a project-based learning approach with a number of hands on activities. The curriculum helps novice engineering students discover engineering and how it shapes the world in an exciting way. It develops the students' engineering skills and practices by teaching them about design through a reverse engineering project based on customer needs, collecting and analyzing data, iteration of solution, computation and programming, team work, etc. The students redesign an everyday product as part of their reverse engineering topic. This topic gives students an engaging learning environment where they can integrate their existing knowledge of different fields of science.

This simulated reverse engineering problem uses an electromechanical device for which the students collect customer needs, identify the redesign opportunity, model the device functionally, use tools to disassemble the product, take measurements (data) when needed, brainstorm solutions with sketches, iterate solutions and build a prototype. They are also required to keep a record with their insights at each stage. The entire project is completed as a team. The curriculum was designed based on the standards of the Texas Essential Knowledge and Skills (TEKS) as dictated by the Texas Education Agency (TEA) and meets a number of standard alignment and state approvals (Texas Education Agency, 2010). The project gives students a good understanding of how engineers work to solve an open-ended engineering design problem.

1.2. OPEN ENDED DESIGN PROBLEMS & DESIGN METHODS

Design problems are approached in different ways in different fields of engineering. As with all design problems, a reverse engineering design problem is open ended, which means that the problem does not have one single or ideal solution. These problems can be solved in a number of ways and with varying levels of sophistication, which are dependent on the resources available. These available resources form the constraints. The engineers need to work within these constraints to develop the best possible solution. Examples constraints include time, money, technology, skills etc.

An example of an open-ended problem in the context of reverse engineering is, 'Redesign a vacuum cleaner to clean liquid waste as well as dust particles'. For this problem statement, there is no one ideal solution. This can be solved in a number of ways. Also, the problem statement itself only defines the end goal, and does not explicitly say what exactly the design is going to be. In order to come up with the best possible solution, a systematic way of thinking must be employed when approaching such a problem. This systematic approach is necessary to keep the engineers focused on the problem and eliminate the complexity that would otherwise ensue. A chaotic approach to problem solving may not result in a solution with clear justification. This systematic way of approaching an open-ended product design problem is called design methodology.

1.3. PRODUCT DESIGN METHODS: AN OVERVIEW

The first documented systematic approach to design education started in Germany with the Ulm Hfg in 1953 (Krippendorff, 2008). A system with a consistent language for design communication and justification, creation of visual records, investigative techniques, statistical tools and other verifiable methods like using experimental techniques to evaluate ergonomic properties were used (Krippendorff, 2008). This produced some innovative solutions and the subject gained popularity. Since then, this focus on design methods has been adopted by mainstream engineering as the profession recognized the value of design methods as a field of study. The study and use of new design methods has seen major growth in the United States since 1990, when the National Science Foundation establish an Engineering Design program.

By definition, design methods are tools that are used to systematically approach an open-ended design problem to create innovative solutions. Design methods are used in both new product development as well as reverse engineering. A new product development effort deals with a problem statement that is not based on any existing single product.

An example of a new product development problem is, 'Design an automatic toothpaste dispenser that caters to the needs of a person with limited motor skills'. This problem statement is open ended and is not based on any existing products. The complexity of such a problem is slightly more than a reverse engineering problem. This is the reason behind teaching the high school students design methods in the context of reverse engineering in the EYW curriculum. Also, the students can start working hands-on with the product from the early stages of the project, keeping their interest level high from the beginning. Working with an existing product provides a concrete context for learning design methods.

An overview of the design methods from the context of reverse engineering is presented here (Otto & Wood, 2001, p. 24-27). A reverse engineering problem typically proceeds through three phases.

1. Reverse engineer
2. Development of a redesign
3. Implementation of a redesign

Reverse Engineer

1. Select a Product
2. Develop a vision
3. Customer Needs Analysis
4. Market Opportunity Analysis

Develop a Redesign

1. Functional Modeling
2. Competitive Analysis
3. Product Architecture Development
4. Concept Engineering

Implement a Redesign

1. Embodiment Engineering
2. Physical and Analytical Modeling
3. Design for X
4. Robust Design

Figure 1: Reverse engineering development process (Otto & Wood, 2001, p.24)

1.3.1. REVERSE ENGINEER

The first stage in the reverse engineering phase of a reverse engineering problem is the selection of a product. For the high school students, the selection of the product must be based on their existing skills and knowledge base. It can also be constrained by cost and safety issues. Typically an electromechanical, everyday product like a hair dryer, toy remote car, coffee maker, etc., is ideal.

Once the product is selected, in the second stage, a thorough customer needs analysis is conducted. Customers are the most important drive behind any product design. This stage involves identifying the customers as well as identifying their needs. This is an extensive stage that involves a detailed study of what the customer likes and dislikes about the selected product. They can also suggest improvements to the existing product directly. Both their dislikes and suggestions for improvements invariably become the customer needs. This stage is very crucial because it dictates the entire direction of the reverse engineering process.

In the next stage, a market opportunity analysis is conducted in order to determine the market for redesigning a certain aspect of the product, which is driven by the customer needs. Once the market opportunity is established for the redesign, the process goes to the next phase of concept development. For high school students, researching the market opportunity can be skipped because the focus here is to teach scientific concepts and not market research techniques. However, the growth of internet-based commerce provides many opportunities for students to benchmark the selected product against competitors and to analyze online reviews for market opportunities.

1.3.2. DEVELOPMENT OF REDESIGN

In the second phase, redesign concepts are developed. In this phase, the product is studied in detail and the concepts are generated. The main stages in this phase are functional modeling, product architecture development, concept generation and concept selection. The first stage in this phase involves completely abstracting the product in terms of what it needs to do vs. how it can achieve it. This abstraction is called functional modeling. The product is broken down into a set of functions that the product has to achieve. By breaking it down to the functional level, the students can identify opportunities for redesign. This abstraction also leads to freedom of thinking because at this level of abstraction, the students are not constrained by any existing ways of solving the problem. This sets the basis for innovative thinking and innovative solutions.

With this vital abstraction for innovation achieved through functional modeling, the next stage of product architecture development is undertaken. For the reverse engineering project this is where the product is completely disassembled, the components are recorded and the product is studied in detail. This stage reveals the existing engineering architecture of the product and also helps identify the areas where the product can be improved by comparing the product with the customer needs.

Once the product architecture is developed, concept generation is started. In this stage, multiple concepts are generated through different ideation techniques. Once concepts are generated in abundance, which is aided by the initial abstraction, the lead concept can be selected. In the context of reverse engineering, the lead concept is the concept that solves the customer needs most effectively while addressing all the constraints. This stage uses certain concept evaluation tools to inform the concept selection.

1.3.3. IMPLEMENTATION OF REDESIGN

In the third and final phase of the process, the lead concept is experimented with, modeled, designed and prototyped. At the experimental stage, there may be certain aspects of the lead concept that have to be verified in order to ensure feasibility, identify an optimal value or simply to confirm that the system behaves in the desired way. There are different ways of experimentation that the engineers use. In the modeling stage, the lead concept is subjected to physical and analytical modeling. This gives insights on how well the concept is going to perform. It also gives valuable information on how the redesign can be implemented in the existing product. The concept design can be modified based on the results of the analysis. This serves as a feedback loop for the concept.

Once the iteration for the redesign is complete, other design considerations should be implemented. This stage is called design for X. The X could be manufacturing, assembly or the environment. So the design is modified taking manufacturing limitations/practices, assembly limitations/practices and environmental concerns into account.

Once the lead concept is finalized, it is prototyped. There are a number of different types of prototypes that can be created. The prototypes provide feedback for improving the final concept. These prototypes can be simple proof-of-concept models to fully functional beta prototypes. The prototype is demonstrated to the customers and their feedback is recorded. The lead concept is again modified using this feedback and a new prototype is created. This is an iterative process. In the end, the final prototype encompassing all the different aspects of the design is created.

1.4. FUNCTIONAL MODELING

Functional modeling is an important tool that design engineers use in order to deconstruct the problem statement and to abstract it to its crux. Functional modeling is performed once the customer needs analysis is completed and a problem statement is formed.

1.4.1. PURPOSE AND MOTIVATION

Functional modeling techniques are used to fulfill two main goals

1. To decompose a complex problem to manage the solution process;
2. To aid concept generation by abstracting the problem.

Any functional modeling technique needs to solve these two main goals. Each of these goals are elaborated here.

Decomposing the reverse engineering problem statement:

In an open-ended problem, there are no right or wrong answers. There are only justified and unjustified answers. In order to be thorough with a product and in order to create innovative concepts without any prejudice, the problem or the product has to be stripped to its bare, essential, basic functions. The overall function also needs to be deconstructed into subsets or sub-functions that can be solved by themselves. This can aid multidisciplinary teams to separate their own sub-functions to work on them individually. This increases the overall efficiency of engineering design work.

Aiding concept generation:

In an open ended design problem, the solution generated by the design team must be justified as the best solution that fulfills the constraints and at the same time answers the customer's needs in the best possible way. In such a scenario, innovation is helpful to fulfill all the conditions. Abstraction of the problem helps in innovation. By abstracting the problem, the designer is not constrained to the pre-existing solutions from experience. The designer has the opportunity to innovate from the abstraction, which provides new ways to solve the problem and in turn helps in generating concepts in a creative and innovative manner.

Prior to the advent of formal functional modeling techniques, design engineers based their solutions for the given problem on their own previous experience. This is highly limiting because it brings a certain amount of bias into the solution. And when there is bias, innovation is affected as it creates a barrier for further exploration. In a way, the designer’s own knowledge can hinder innovation. Once the problem is presented in the form of the customer needs, the designers start thinking of systems and components that can solve these needs, based on their previous experience. Essentially they are looking at 'how' to solve the problem. And that question is readily addressed by the previous systems that they have seen from their experience. Once they relate these needs to those systems, the problem is solved. There is nothing that drives them to look further. They just evaluate the solution by determining if it solves the customer needs. If it does, it becomes their 'best' solution. But there is no way of knowing whether the solution is indeed the best, given the nature of open-ended problems. However experienced these design engineers might be, their creativity and innovation are limited by asking the question 'how'. The flow of this process is represented below.

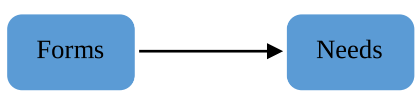


Figure 2: Form addressing needs

The form is the existing solutions that the design engineers are familiar with. Once the forms address the needs, the process stops. Another disadvantage of this approach is that the customer needs are merely used as a means to evaluate a solution rather than a means to generate solutions.

In order to solve this problem and to promote innovation, design engineers have to abstract the problem. Instead of asking 'how' to solve the problem, they instead need to ask the question 'what' needs to happen. The needs have to be converted into functions and then into forms. The flow becomes

Figure 3: Function based on needs

This function is an abstraction of what the product needs to do. The overall function of the product is abstracted as well as multiple lower-level sub-functions that combine to solve the overall product function. The definition of a product function, as given by Otto and Wood (2001) is as follows: 'A function of a product is a statement of a clear, reproducible relationship between the available input and the desired output of a product, independent of any particular form.'

Product function is the most abstract way of looking at the product in a simple way. A product function is stated in verb-object format, sometimes modified by an adjective. Examples include 'grind coffee', 'remove dirt', and 'project light'.

This overall product function can usually be decomposed into many sub-functions. A functional modeling technique can be seen as a tool used to identify these sub-functions and their interaction with each other. These sub-functions are also expressed in verb-object format. Examples of sub-functions are 'store electrical energy', 'transfer water', 'heat air', and 'convert mechanical energy to electrical energy'. Ideally, these sub-functions can be worked with separately without affecting the other sub-functions. This is how the problem is decomposed.

These sub-functions are arranged in a sequence that follows the order in which the sub-functions must be executed. This interaction between the functions is important because it gives an overarching view of what the product needs to do and in what order.

These functions are very abstract. The abstraction comes from the focus on the 'what' of the problem instead of the 'how'. By abstracting the problem to the 'what', a number of 'hows' can be envisioned. This is how functional modeling aids in innovation in a reverse engineering problem.

Two common functional modeling techniques that are used by design engineers are function trees and function structures. Each of these methods has its advantages and disadvantages. Both of these techniques are described briefly below.

1.4.2. FUNCTION TREES

Function trees are the simplest way of functional modeling and are very easy to build. Two main approaches to developing function trees are The Function Analysis System Technique (FAST) method (Otto & Wood, 2001, p. 154-159) and Subtract and Operate Procedure (Otto & Wood, 2001, p. 159-162). Both of these methods employ a brainstorming approach for identifying the functions in a system, though the FAST method adds some structure to the process. Both these methods, however, lack explicit representation of sequencing and interaction between the functions, which is an important attribute. Also, there is no explicit tie between the functions and the customer needs. Though this is a simple tool that can be used to quickly identify the abstract functions of a product, it does not provide the detail that is provided by function structures. The simplicity is gained at the expense of compromising the understanding of interactions between functions.

1.4.3. FUNCTION STRUCTURES - BLACK BOX

The function structure is developed in two steps:

1. Black Box
2. Function Structure

The first step in creating a function structure is creating a black box model. A black box is a tool that is used to identify the overall product function, system boundary and the inputs and outputs of the system (Otto & Wood, 2001, p. 162-165). After defining the product function, the system boundary is set. Then the inputs and the outputs are identified in the system. The inputs and outputs of a typical electromechanical system are of three types:

i. Energy
ii. Material

iii. Signal

An energy input is a type of energy that the system requires in order for it to perform its function. This energy is transformed by the system and exits as the desired energy output. A material input is matter that the system accepts in order to perform its function. Some materials are changed to a different form as dictated by the customer needs into desired output forms. Other required materials are accepted and exit the system unchanged. A signal input is information that is accepted by the system to perform its task. The system may provide signals as outputs as well.

All three categories need to be identified and recorded. A black box is an ideal way of representing this. This tool is used to capture the input and output energy, materials and signals of an electromechanical system. It gives an overview of the inputs and outputs of the product in a very abstract way. The term 'black box' refers to the opacity of the internal workings of the system, as it only shows inputs and outputs. At this point, the design engineers do not model what happens inside the system. The step-by-step procedure for building the black box is shown in the Appendix I with an example. This is a very simple tool and very easy to understand and implement by high school students. This sets the groundwork for the next stage of developing function structures, which can be thought of as expanding what happens inside the black box based on its inputs and desired outputs.

1.4.4. FUNCTION STRUCTURES

The function structure is a thorough functional modeling tool that takes into account the energy, material and signal flows. This tool addresses the limitations of function trees in recording the interactions between the functions while also basing the functions on the customer needs and customer interaction with the product. This makes the tool a lot more sophisticated than the function trees. The function structure deconstructs the problem statement in a detailed way. By recording the interactions between the flows, a high level of abstraction and detail is achieved.

Development of a function structure proceeds through five steps (Otto & Wood, 2001, p. 166-177), each of which is described below.

1. Phase 1 - Develop process descriptions as Activity Diagrams.

   In the first phase, the Activity Diagram is developed. This is a representation from the user's perspective of the entire product cycle from purchase to disposal. An activity diagram captures three phases of product use: preparation, execution and conclusion. The activity diagram accounts for the choices made by the customers when interacting with the product. The activities in the activity diagram aid in formulating the sub-functions of a function structure. The sub-functions can be thought of as the responses of the system to user activities. An example of an activity diagram for a fingernail clipper can be found in Appendix II.

2. Phase 2 - Formulate sub-functions

   In this phase, each of the activities and the customer needs are converted to flows. These could be energy, material or signal flows, depending on which are to user activities or customer needs. Some customer needs cannot be conceived by functions. These become constraints to the redesign. Cost, time, material properties, technology, and skills examples of customer needs that do not translate readily into product functions.

3. Aggregate sub-functions into a refined function structure

   In this phase, the sub-functions that were identified in the previous step are combined to form the complete function structure. For some products there can be multiple function structures depending on choices of flows or other process choices. The function structure as a whole should meet the customer needs along with the constraints.

4. Validate the functional decomposition

   This is an iteration of the function structure where the function structure and the customer needs are compared. An important validation criterion is that the sub-functions should be "atomic", meaning they each have independent solutions. More sub-functions are added and unnecessary sub-functions are removed.

5. Establish and identify product architecture and assemblies

In this phase the entire function structure is analyzed in order to identify possible sub-assemblies and modules. This provides a basis for the team to separate the design tasks in a cross-functional manner. An example of a function structure for a Nerf Blaster is shown in Appendix III.

It should also be noted that while the flows are based on the customer needs, they are independent of the components. The function structure only records *what* has to happen and not *how* it should happen. The gap between these two allows designers to use their creativity to respond to the customer needs. This is how innovative solutions can be created.

1.5. THE PROBLEM

With so many advantages, the functional modeling is ideal to be used for a reverse engineering problem in order to improve innovation. But in the context of high school and novice engineers, this tool poses some problems.

For the high school students, function structures can be complex. The difficulty arises from a number of aspects. The effective usage of this tool requires a certain level of understanding of different systems. The designer needs to be familiar with the different energy forms and its transformations. They need to know about different signals and how they can be used. The flow diagram itself can get complex at times. It is potentially overwhelming for someone learning the tool without an engineering background.

Despite its complexities, this tool should not be taken out of the curriculum. Learning about problem decomposition and abstraction for innovation is an important aspect of engineering design that the students should learn. In order to solve this problem, a new study was undertaken to create a new way of using the functional modeling technique that specifically caters to high school students learning design methodology.

1.6. HYPOTHESIS

The new functional modeling technique for novice engineering students must be developed to fulfill certain conditions:

i. It must be simple and intuitive to use

ii. It should decompose the problem

iii. It should abstract the problem in a way that leads to innovative thinking

iv. It must be easy to integrate into the curriculum without drastic changes

With these four conditions in mind, a multi-stage study was undertaken. The stages of the study are explained below.

In the first stage, interviews were conducted in order to determine whether students think in terms of functions intuitively. This is a defining question that shows whether the functional modeling technique that needs to be developed can be based on existing techniques, or whether a completely new technique has to be developed. This study solely on energy functions. The hypothesis is that energy flows and their transformations are the main functions in many devices and are more intuitive to visualize. While signals and material flows are important, focusing on energy flows provides the students a natural approach to generating alternatives. Interviewees demonstrated that they are able to stop thinking simply in terms of ‘how’, and can think in terms of ‘what’ which is central to functional modeling.

In the second stage of the study, based on the results gathered from step one, the new functional modeling technique was developed and tested first with high school teachers in order to gain their feedback. Testing the technique with high school teachers was a vital step, as they are the ones who will be teaching the new technique. Their understanding of the technique and its ease of use are as important as their student's ease of use. Their insights were very valuable and were used to guide development of the tool. Their comfort using this technique provided a validation for the new functional modeling technique.

The final stage of development was evaluation by novice engineers. At this stage it was expected that students would find this technique simple and effective to use. They were tested on their ability to deconstruct the problem and also on their ability to abstract the problem before and after the technique is introduced.

With this final feedback, the tool was further revised and the final version is recommended for adoption in the *Engineer Your World* curriculum.

1.7. THESIS ROADMAP

This thesis is arranged the following way.

Chapter 1 - The problem background was presented in this chapter, including existing functional modeling tools.

Chapter 2 - The literature review is presented in this chapter. It explores the limited literature available on functional modeling in high schools.

Chapter 3 - In this chapter, the initial study presents the basic questions about functional modeling and how it affects the expert vs. novice criteria.

Chapter 4 - Here, the methodology that was developed based on the findings from the initial study is discussed in detail. It also presents the feedback gained from implementation in a professional development program for high school teachers.

Chapter 5 – This chapter presents the evaluation phase where the revised tool was used by novice engineers to gain feedback on the effectiveness of the tool.

Chapter 6 - This chapter presents conclusions and recommends future work to improve the functional modeling technique.

CHAPTER 2
LITERATURE REVIEW

2.1 LITERATURE SURVEY AREAS

Preliminary literature searches soon made it evident that there was very limited existing research on this highly specific topic of teaching functional modeling in high schools in the context of reverse engineering. As a result of this limitation, the literature review was expanded to include other aspects of the problem of teaching functional modeling in high school and in order to gain an overall picture and climate of engineering education in schools.

This literature review provides background for understanding functional modeling, design methodology and high school engineering focused on design. This background research gave a wide range of insights on the current status of the research and what needs to be done in order to progress from here. It gave a bird's eye view of the problem that this research addresses.

The literature review was focused on three areas.

1. Engineering in elementary, middle and high schools
2. Engineering design in high schools
3. Functional modeling in design education

Engineering design research is very broad in its scope. The research was limited to how engineering started in high schools, what topics are covered and the goals of pre-college engineering education. One of the major topics that is covered in high school engineering curricula is engineering design. Design is one of the most fundamental aspects of engineering. As it is such a vital aspect, it is unsurprisingly introduced when engineering is taught at a high school level. Again, design itself can be broad. Specifically, product design is adopted because it is easy to understand and at the same time, teaches the engineering methods that engineers use.

Project-Based Learning (PBL) is preferred in order to teach high school students basic principles of engineering. This stands to reason since high school students have a very limited understanding of actual engineering principles and engineering itself is a very broad field. By incorporating project-based learning, students have hands-on experience which can then be used to learn the principles in a much more intuitive manner.

Reverse engineering is one way of providing a project-based learning environment. Reverse engineering uses an existing consumer product, which is disassembled by the students, paving the way for them to learn about particular technology and broad engineering principles. The selection of the product itself is crucial because complex products may overwhelm students, while a simple product may not capture their attention. The selection of the right product plays a major role in this research. The literature survey revealed the different approaches used in high school engineering curricula to teach reverse engineering. It also revealed ideas of different products that can be used for the current research on functional modeling.

One of the main topics in design methodology is functional modeling, which is the central research topic for this thesis. Research on functional modeling in high school itself is very limited. This may be due to the fact that people have left out functional modeling in other high school curricula because of the complexity of the technique. Also, existing modeling techniques are indeed very complex and even engineers with a lot of experience can struggle with them.

2.2 ENGINEERING IN ELEMENTARY, MIDDLE AND HIGH SCHOOLS

Research K-12 engineering education in revealed some key insights. The first major advantage of K-12 engineering education is that learning engineering improves overall learning ability. This is simply because children by default learn through experience (Benenson, Apostoleris, & Parnass, 1997). By practically applying what they learn in their science and mathematics classes, the student makes the connection between the abstract science and the real world applications, thereby increasing interest and performance. Also, project-based learning in engineering is learned through experience, more specifically, hands-on practices. This makes engineering an attractive field to students. The second major advantage is the variety of career paths that STEM education leads to (Genalo, Bruning, & Adams, 2000). Exposure to engineering might cause students to choose the path of STEM as a career. This not only helps to solve the problem of 1.2 million STEM vacancies by 2018 (Langdon et al., 2011), but also creates more interesting and exciting career options for students. Teamwork and leadership skills development are other major advantages of project-based engineering curriculum. This helps students develop strong leadership skills. As engineering is a multidisciplinary area, students actually see how different subjects that they have learned come together to make a tangible difference. This helps them see the importance of other subjects and possibly increase their interest in them as well. For all these reasons, engineering is an ideal platform to teach STEM in K-12.

Research on engineering education in K-12 has led the way to a number of curriculum developments designed to expose K-12 students to engineering. Children are exposed to engineering as early as first grade (Portsmore & Rogers, 2004). Literature reviews on engineering taught in elementary, middle and high school revealed that they are all broadly focused on the same goals. There are generally two goals of teaching engineering from early childhood: (1) to educate the future and (2) to meet the growing demand for a scientifically literate population (Sanoff, 2001).

Most pre-college engineering education is through outreach programs. A study of K-12 engineering outreach programs (Jeffers, Safferman, & Safferman, 2004) reveals the common themes in these programs. The authors summarize 60 different outreach programs that contain the common theme of activity based learning with a focus on younger students. In general, the trend is to start engineering education in elementary school in order to expose the next generation to science and technology that will transform the future (Cunningham, 2007). Cunningham, director of the Engineering is Elementary® program of the Museum of Science in Boston, MA, writes, "Children are born engineers—they are fascinated with designing their own creations, with taking things apart, and with figuring out how things work..." This is the basis of starting engineering education at a very early age coupled with the demand for engineers in the US job market. There is a huge demand for students to be educated in STEM fields (1996 NSF Report).

Elementary and middle school teachers generally cannot be expected to incorporate engineering principles in their classes. The scientific community of researchers, engineers and scientists are constrained to their universities and labs. , Outreach programs have been developed to bridge the gap (Ondracek & Leslie-Pelecky 1999). Introduction to engineering happens as early as first grade. The Engineering by Design program from the Center for Engineering Educational Outreach (CEEO) at Tufts University used LEGO® to teach first graders the basic principles of engineering. CEEO was also a leader in engineering outreach at the higher elementary grades through the development of the ROBOLAB programming environment for the original LEGO® MINDSTORMS® product. CEEO created an outreach program based on ROBOLAB in collaboration with LEGO (LEGO Group, Billund, Denmark) and National Instruments (Austin, TX). A big advantage of this program was the flexibility and the cost effectiveness of the entire toolkit. The LEGO kit along with the software developed by the NI can be used in multiple ways, which gives a certain level of design freedom that elementary school students can explore. (Portsmore & Rogers, 2004)

A noteworthy outreach program for middle school is the Engineer Your Future program, which was a collaboration between IBM (Armonk, NY), Colorado School of Mines and the Denver (CO) public school system. This program used a simulated engineering problem where the students worked together as a team to brainstorm a design using different polymers in designing diapers. More recently, two programs in the elementary and middle schools stand out: Engineering is Elementary®, mentioned above, and In the Middle of Engineering, a program offered by the National Girls Collaborative Project (Seattle, WA). Both these programs introduce the students to engineering and technology at a very early age by incorporating engineering principles into their coursework (Rivoli & Ralston, 2009)

Traditionally engineering was not a part of K-12 education (Cunningham, Knight, Carlsen, & Kelly, 2007). In order to promote engineering in middle and high schools, teachers first require training in the engineering principles used before they can incorporate them in their classroom curricula. The Pre-Engineering Instructional and Outreach Program advocates teacher training in engineering and educates students, teachers and parents on the options that come with engineering education (Hirsch, Kimmel, Rockland, & Bloom, 2005).

It should be noted that, irrespective of the target grades, the approach to pre-college engineering is mostly activity based learning. Though the main idea behind introducing engineering design in elementary and middle school is to promote interest and knowledge in STEM education in students, these programs are designed only to give a sense of what engineers do in general. These programs generally do not delve deeply into any kind of engineering methodology, and in particular, functional modeling.

In 1996, National Science Foundation report showed a huge demand for engineering education in high schools. Robinson, Fadali, Carr, & Maddux (1999) report on the design and implementation of a capstone engineering course to address this increasing demand. An approach to train in-service and pre-service teachers in engineering principles with capstone projects was first introduced. It was found that the participants' attitudes towards engineering improved significantly after they experienced the capstone program was introduced. The program is different from an outreach program in that it provides credits that count towards the degree that the participants were pursuing. The capstone program is designed to provide practice in engineering rather than teaching engineering theory. This was a way to prepare teachers to incorporate engineering principles in their own classrooms.

Research on engineering education in high school has led to a number of curricula developed to expose high school students to engineering. Some of the major high school engineering are Project Lead the Way, the Infinity Project, and TeachEngineering.

Project Lead the Way (PLTW) is considered a premier non-profit organization that provides engineering curricula to middle and high schools in the US (McVearry, 2003). They use project-based and problem-based learning where the students are encouraged to learn by discovery. The Infinity Project was developed by Southern Methodist University in collaboration with Texas Instruments (Dallas, TX). They use hands-on methods to teach engineering, particularly focused on digital electronics. TeachEngineering (https://www.teachengineering.org/) is an online K-12 engineering curriculum repository. TeachEngineering provides single day modules, a week-long program, and a complete course in engineering that cater to middle and high schools. The UTeach*Engineering* program is a recently developed curriculum that is aligned with Texas standards for high school engineering (Farmer, Allen, Burland, Crawford, & Guerra, 2012).

2.3 ENGINEERING DESIGN IN HIGH SCHOOLS

Engineering is a very broad area. There are a number of different fields of engineering including electrical engineering, mechanical engineering, petroleum engineering, chemical engineering, computer engineering and nuclear engineering, to name a few. Though each of these different fields of engineering has its own vast knowledge base, all of them follow the basic inquiry-based exploration. This is the key principle that is taught in K-12 education. And in order to teach these engineering practices, the field of engineering design is used (Oden et al., 2006). Two different research studies corroborated in their findings that design-based learning enhances students' abilities in problem-solving and increases their scientific enquiry skills (Kolodner et al. 2003; Silk, Schunn, & Cary, 2009).

Almost all high school engineering curricula utilize a design-based approach in teaching engineering. They use design projects to teach students the engineering design principles. The intention is to allow students to learn science and mathematics in the context of learning design applied through engineering practices (Apedoe, Reynolds, Ellefson, & Schunn, 2008). Design itself is a very broad area and is taught in every field of engineering. Simple, everyday products can be designed or reverse engineered in a classroom setting. These project-based and problem-based activities encourage students to learn by discovery.

The Project Lead the Way (PLTW) curriculum incorporates a one year long capstone project that integrates the skills that the students have learned in previous years to solve an open-ended problem. The program has modules on engineering design and development where the students work in teams to develop solutions to proposed open-ended engineering design problems using the engineering principles taught (Blais, Adelson, 1998). The Infinity Project employs active learning by developing software for a National Instruments hardware platform to analyze audio and video signals (Orsak et al, 2001).

The *Engineer Your World* curriculum from the UTeach*Engineering* program uses reverse engineering as part of the hands-on approach to teach engineering design practices. The curriculum takes complete advantage of active learning practices and introduces design problems in stages. The stages vary with the complexity of the problem. The curriculum starts with a simple pinhole camera, moving on to hands-on exploration of the design of building models based on earthquake simulations. Then the students reverse engineer a human-powered flashlight. Finally they design an aerial imaging system (Harris, 2015).

2.4 FUNCTIONAL MODELING IN DESIGN EDUCATION

The very first usage of functions in a product started more than 70 years back. In the 1940s, Value Engineering used functions of the product to identify redesign avenues. By associating manufacturing cost to each of the functions, Value Engineering identifies the function most likely to provide an opportunity to be redesigned to reduce the cost (Miles 1972; Akiyama 1991).

Modern research on functional modeling started around 1980 when functional vocabulary became a research topic. There were a few researchers that started standardizing the functional vocabulary. The general definition of function was given by Pahl and Beitz (1984) as an input/output relation of a system to perform a task. The functional grammar was first introduced in 1987 which uses verbs to describe a function. This paved way for combining multiple parts with a single function, thereby abstracting the problem (Lai, Wilson, 1987). The functional representation of a redesign problem was used in redesigning the reaction wheel assembly of the Hubble space telescope. They used structure-to-function maps that capture the structure of the component, its function and relates them as a way to organize the problem (Goel, Chandrasekar, 1989).

The function-behavior-state is a method of hierarchical arrangement of functions, behaviors and states that captures the abstraction and the user interaction, as well as the structure of the device. The key factor in this method was the development of a computer tool that helps in creating these models more efficiently (Umeda, Tomiyama, & Yoshikawa, 1995).

Function structures, defined in Chapter 1, were first introduced by Pahl and Beitz (1977), and later in the English translation (Pahl & Beitz, 1984). Their methodology starts with an “overall function”, which is essentially a black box model, which is then decomposed into a complete function structure with sub-functions and material, energy, and signal flows. Based on their work, Stone and Wood (1999a, 1999b) created a function taxonomy called the functional basis. This provides a framework for comparison of function structures created for different products.

CHAPTER 3
INITIAL INVESTIGATION

3.1 INITIAL STUDY

A pilot study was conducted that focused on answering some basic questions about students' learning methods with respect to functional modeling, when introduced for the first time. It was necessary to conduct the study with students who had not been introduced to any functional modeling techniques in order to find answers for these three driving questions:

1. Do students think in terms of functions in engineering design by default? Or do they think in terms of components by default?
2. How much does the level of science education and understanding of different energy systems help in thinking functionally? How strongly are they related?
3. Does thinking in terms of parts/components first allow students to recognize functions more efficiently?

It was important to understand the thinking process of the students when they are learning about functional modeling. The study provided insights on how they abstract the product and its functions. Understanding this was vital in designing the new functional modeling tool.

3.1.1 RATIONALE BEHIND QUESTIONS

These questions were formulated based on the main goal of understanding the students' ability to think in terms of functions. They also test hypotheses on how much thinking in terms of components first helps them recognize functions. The rationale behind each of these questions and the implications of the possible findings are discussed here.

1. *Do students think in terms of functions in engineering design by default? Or do they think in terms of components by default?*

This is the most important question that drives the initial study. By knowing whether students by default think in terms of functions or whether they focus on the components first, a decision could be made about whether a new functional modeling technique has to be created or the existing functional modeling technique can be modified to fit the need of students. If the findings show that they already think in terms of functions by default, a tool that follows the same pattern of function structures can be developed. The existing functional modeling tool must be modified in order to make it simpler for the high school students/novice engineers to understand. In this case, there would be no need to develop a drastically new way of functional modeling. If it was found that students do not think in terms of functions, and they only relate to the physical components, then a new way of teaching functional modeling must be developed. This new model would need to have a way of relating the components to recognize functions and create the functional model from them. Depending on the findings from this question, the entire curriculum could potentially change in terms of product used, time to teach the curriculum, addition of new tools, rearrangement of the design process, etc.

2. *How much does the level of science education and understanding of different energy systems help in thinking functionally? How strongly are they related?*

One of the biggest concerns in teaching function structures is the students' level of science education, specifically in understanding of different energy systems. In order to find the gap between the existing level of science education by a high school level student and the level required in order to apply functional modeling effectively, it is essential to understand if this level of science education affects the students' thinking in terms of functions. This question also helps determine the degree of difficulty of science topics, specifically with respect to different forms of energy and their transformations that have to be included in the curriculum to scaffold the students' scientific understanding. The findings from this question will also aid in the selection of the product to be implemented in the curriculum. The product selection should be based on the level of scientific understanding that can be taught in the limited time provided for lectures in the curriculum.

3. *Does thinking in terms of parts/components first make them more efficient in recognizing functions?*

This question is an attempt to find out if thinking in terms of components helps students think in terms of functions. It is possible that the students do not recognize the concept of functions. In order to aid them in recognizing functions in such a scenario, a study of physical components may trigger them to think of the functions of the components. Once the function is recognized, a decision can be made to replace the part/component with another component that can fulfill the same function in a more desirable manner. Answering this question will give an insight into whether the students need prompting during the learning process to keep them thinking functionally and stop them from straying into the component thinking. It could be tricky for them to see the difference. This might be the biggest challenge of teaching functional modeling.

3.2 CLINICAL INTERVIEWS

In order to elicit answers to the three main driving questions, clinical interviews were conducted. Clinical interviews are a method of interviewing that explores the thinking of the students when they are solving a problem. The technique is used in the field of psychology and was developed from learning science and cognitive science research (Ginsberg, 1997, p. 9). This approach gives insight into how the interviewees, who may be either scientifically literate or scientifically disinclined, learn and show their limitations. This interview method follows certain rules.

1. It needs to be accompanied with a task protocol.

This task protocol is a set of rules and guidelines explaining the problem to the students. The task protocol needs to be clearly defined and time bound. It is good practice to walk subjects through the task protocol before the start of the interview.

2. No leading questions

Most of the understanding of the students' learning comes from observation and asking questions. In order to keep the interview neutral, questions must be as neutral as well. Leading questions must be avoided because that might elicit a biased response.

3. Record the response, take notes

It is important that the entire interview be either video recorded or audio recorded. This allows a more detailed analysis of responses. Also, the interviewer needs to take notes on the students' responses throughout the interview. Clinical interviews are ideal for the study because functions are a way of thinking, and there is a process to this thinking. The understanding of this thinking process may lead to a new functional modeling technique.

During the clinical interviews for the initial study, the students were first walked through the task protocol and were asked to complete certain tasks that were designed to develop a functional model. The interviews were video recorded. Questions were asked during the interview that were focused on probing deeper into what and how the students were thinking. The students were interrupted from their tasks when needed to ask probing questions. Leading questions were carefully avoided. Notes were taken.

3.2.1 ENERGY FLOW

Testing function structures directly with the students is not feasible for a few reasons. The technique is complex and can be confusing at times. Asking the students to create a function structure for the clinical interview would be time consuming, taking time away from direct questioning of the participants. Some important questions might not be asked because the participants could be caught up in the complexity of the tool.

In order to simplify the clinical interview process and to make the most efficient use of questioning, only the energy flows within the system was considered. The material and the signal flows were disregarded. The function structure now has just energy flows and is simple to use while maintaining the abstraction and decomposition of the problem, which is the main reason functional modeling is used. So the students were instead asked to represent the energy flow inside the product in the form of an energy flow diagram similar to function structures.

This had to be done in two stages. In the first stage, they were asked to predict the energy flow before disassembly of the product. In the second stage, they were asked to draw the actual energy flow after disassembly and analysis of the components inside the product. The first stage gave insights into whether they think in terms of functions or not. The second stage determined whether they can abstract the functions of the components. This process took a lot less time for them to work on and a lot more time for the actual clinical interview process. The idea of using just functions acting on the energy flow can also be developed further as a new functional modeling technique based on the results of the interviews.

3.2.2 SELECTION OF THE PRODUCT

The selection of the product is one of the most vital parts of the entire study. In order to give the students ample opportunity to explore and at the same time help gain valuable insights based on multiple functions, the product had to fulfill five criteria:

1. The product needs to have at least four different energy conversions.

   A device that has as many conversions as possible was required to increase the chances of the interviewees recognizing as many as possible. These four energy conversions are the four functions performed by the device from the energy transformation perspective.

2. The energy conversions inside the product must have at least three types of conversions.

   The product needs to have energy transformations with some variety rather than just one or two types of energy conversions. This is important to gain insights into the interviewees' breadth of knowledge about different energy systems and their transformations.

3. It should be based on a high school level of science/technology knowledge.

The product selected for this initial study has the potential to be the actual product used in the curriculum for learning functional modeling. So the level of science and technology involved in the working principle of the product should not be greater than a high school student's level of understanding of energy and its transformations.

4. It must be easy to disassemble and assemble the product.

When selecting the product, it should be kept in mind that the students are going to disassemble it in order to build their actual functional model. So the product should involve relatively few steps and little time to disassemble and require only simple and safe tools to aid the disassembly process.

5. It should appeal to all genders

The product selected should not be biased to one gender of the population. The product should cater to everyone. It should hold the interest of any gender.

The product currently used in the *EYW* curriculum, which fit all of the above criteria, is the hand cranked flashlight.

Figure 4: Opaque hand cranked flashlight

Figure 5: Transparent hand cranked flashlight

The product has eight different energy conversions. There is a good variety of types of energy transformations that require basic knowledge about gears (mechanical energy), electrical generators (electrical energy), light bulbs (light energy and heat energy), etc. It also has human energy as an input. All the energy transformations are very basic and can be easily understood by high school students. There are no complex components or energy transformations. The parts that can be considered the most complex are the generators, which are a very common part used in variety of household products.

Another advantage of this product is the availability of a transparent version of the same device. This added the advantage of flexibility during the interviews where it was possible to shift between the two products without the necessity of disassembly. The opaque flashlight was considered assembled and the transparent flashlight was considered disassembled as it is easy to see the parts/components and the internal workings of the product through the transparent cover.

Both these devices have the same exact components inside and they work the same exact way except for one minor difference. The opaque flashlight has a built-in storage battery and the transparent one does not. This was ignored because it was not necessary to follow the function/energy flow of the battery and the questioning can be focused on the conversion of human energy to light energy. This is considered a gender neutral product because of its unisex design and usage. The initial reaction from the interviewees confirms the gender neutrality of the product. They all found it equally interesting.

The disadvantages of the product are that some interviewees may not be very familiar with the working of the generator, which is the most complex part of the system. Additionally, a flywheel is mounted on the same shaft as the magnets for the generator. This might confuse students who might actually be familiar with generators and wonder where the magnets are, as they are beneath the flywheel. There are also multiple gears inside the device. Though they are all essentially used to convert the human energy input to mechanical energy and increase the speed of the flywheel, each of these gears serves its own function of either increasing or decreasing the speed or torque. This might confuse the students. To avoid confusion during the study, the participants were not expected to go into that level of detail.

The small size of the opaque flashlight and the relatively larger size of the transparent flashlight might confuse them a little bit, but essentially the devices perform the same energy transformations. Only the amount of energy itself changes. The energy flow/function flow of this device can be seen in Appendix V for reference.

3.2.3 INTERVIEWEES SELECTION

In order to conduct this clinical interviews, four undergraduate students from The University of Texas at Austin were selected. Undergraduate students were used because they were readily accessible. They were also novice engineers because none of them have any formal training in engineering discipline.

These interviewees were selected based on the expert and novice criteria, driven by the second research question aimed at understanding the level of scientific education that affects functional thinking among high school students.

	Part list	No Part list
Expert (Science major)	Bruce (Computer Science major)	Richard (Physics major)
Novice (Non science major)	Mary (International Relations major)	Rose (Business major)

*Names have been changed for anonymity.

Table 1: Interviewee List

In this study, in the context of high school students, experts are the ones that have a better understanding of scientific principles behind energy and its transformations than high school students who received A's in science. It is ideal to have a science student who is either a sophomore or junior in college. The novices can be students who have graduated high school at least two years ago and are not in the science track. This is to make sure they are not as familiar with the subject, but can be prompted to think if there is a need. Non-science students in the sophomore or junior year are ideal for this category.

Of the four interviewees selected, two of them were science students and two of them were non-science students. Two of them were male and two of them were female. Their ages were between 19 and 21. All of them were in their sophomore year of college.

Two of the students, Bruce and Mary, an expert and a novice, were asked to think of the parts list before thinking in terms of functions and the other two, Richard and Rose, again an expert and a novice, were asked to come up with functions directly without thinking about components first. This was to gain insight on the third question of whether thinking in terms of parts and components helps in formulating functions. So a total of four categories were created. Each of the interviews was different from the others.

One thing that can be noted in the interviewees list is that both of the experts were male and both the novices were female. This 'should not affect the data collected because the criteria are only based on level of expertise and not gender. The only place where gender was considered was in the level of interest in the product. It was found that all four of the interviewees were equally interested in the hand cranked flashlight.

3.3 TASK PROTOCOL

The task protocol was developed in order to conduct the clinical interviews. It lists tasks to be completed during the clinical interviews and the time allotted for each. The protocol has to be followed in that specific order. The protocol consists of two tasks, each of which has its own line of questions/focus. All four interviewees must complete both tasks. The task protocol is presented in Table 2.

Task 1	Give interviewee an electro-mechanical product (Opaque hand cranked flashlight)
i	Let them study the device (2 minutes)
ii	Ask them to describe what it does (8 minutes)
iii	Ask them to list the parts inside - Only for one of the experts and one of the novices (10 minutes)
iv	Ask them to describe the energy flow (15 minutes)
v	Ask them to list other components that can be used for the same energy flow (15 minutes)
Time	50 minutes
Materials needed	Pig flashlight, paper, pens
Task 2	Give interviewee an electro-mechanical product (Transparent hand cranked flashlight)
i	Ask them to list the parts that they see – Only for one of the expert and novice (10 minutes)
ii	Ask them to describe the energy conversions (15 minutes)
iii	Ask them to list other components that can be used for the same energy flow (15 minutes)
Time	40 minutes
Materials needed	Transparent flashlight, paper, pens

Table 2: Task Protocol

3.1.1 RATIONALE BEHIND TASK PROTOCOL

TASK 1:

For the first task, the first two subtasks were based on structural thinking. They were meant to make the interviewees thoroughly examine the device. The main reason behind this is to see if the students can figure out how to operate the device. This holds the key to them understanding that human energy goes in as input. This is important because, when the device is in its packed stage, the crank is flush with the side of the product, and a hand operated flashlight is not a common device. This would give valuable insight into how quickly the interviewees find out about the human energy is the input, and to see if they consider human energy as an actual energy. It is very important that the high school students learn that in functional modeling, human energy, even though mechanical in nature, is always categorized distinctly because of the importance of human interaction with consumer products. Also, many products can be redesigned to be automated to reduce human interaction. But first the human input needs to be identified. It is also not intuitive to view human input as a form of energy. This question will reveal their thinking process about human energy as an input.

The third subtask, listing the parts that they think are in the product, was meant to test their ability to predict the components inside. It also provides insight into their level of understanding of energy conversions/functions. This question was asked only to one expert and one novice to determine whether thinking about parts first makes any difference thinking in terms of functions. This addresses the third driving question of the study.

The final subtask for task 1 was intended to encourage the participants to think in terms of functions. Functions in an electromechanical system mostly comprise energy conversions. So instead of asking them about the functions performed inside the device, the question was instead focused on the energy conversions in the device.

These are the major functions performed of the device. Changing the wording is meant to reveal whether they realize they are thinking about functions. Task 1 was designed as a pre-disassembly task. Task 2 comprises the post-disassembly questions.

TASK 2:

Task 2 involved disassembly of the hand cranked flashlight to see how it works. But instead of disassembly, in order to save time and to simplify the process for the interviewees and in order to focus on the driving questions, a transparent flashlight was used instead. The interviewees could see the components and their operation through the transparent cover. The first subtask, like in task 1, was asked of only one expert and one novice. This subtask in task 2 was included for the same reasons as in task 1, which is to determine if thinking about components first makes any difference in thinking about functions. They were expected to identify a more comprehensive list compared to the predicted list from the opaque flashlight. The second subtask is similar to task 1, with the difference that the answer was expected to be more comprehensive.

The third subtask of asking them to list the components that could be used instead the current ones, was meant to provide insight into whether they retain their functional thinking and come up with better feasible solutions. This subtask tested their ability to retain a functional view while looking for other ways to solve the function, and to determine whether exposure to the components constrained them in any way from creative thinking.

It should be noted that these are just the guiding subtasks. There were a lot of additional questions that were asked on the spot in order to gain insight into how they think and learn when it comes to functions. Most of these questions were based on what they were saying or drawing at that particular time.

3.4 RESULTS

The clinical interviews were conducted based on the framework of the task protocol. The task protocol was strictly followed. Each interview took an hour and a half and provided valuable insight into the student's way of thinking when dealing with product functions and sub-functions.

The results of the study were quite interesting. The findings for each interviewee are discussed separately.

EXPERT - NO PART LIST:

The first interview was with Bruce. He is a Computer Science major in his sophomore year and is considered an expert in this study. He formed the first category by going through the task protocol without the parts list. The summary of the results are:

1. Describe the hand cranked flashlight in detail
2. Came up with a reasonable list of energy conversions (5 conversions out of 8)
3. Did not recognize the difference in converting one form of mechanical energy to another form
4. Came up with two alternates for a specific energy flow.

These responses and the level of detail were expected from him. The most interesting thing about this interview was the fact that he was not able to recognize the difference in conversion of one form of mechanical energy to another form of mechanical energy. He was able to recognize the conversion of completely different forms of energy. This could be because he was focused on different energy varieties and not simple energy modifications.

EXPERT - PART LIST:

The second interview was with Richard, a Physics major in his sophomore year. He was asked to list the parts/components before creating the energy flow, forming the second category. Here are the findings.

1. Describe the pig flashlight in detail
2. Came up with a reasonable list of predicted parts (5 parts out of 12)
3. Came up with an additional energy conversion compared to Bruce, the expert with no part list (6 out of 8)
4. Came up with two good alternates for a specific energy conversion

It is interesting to note that when he focused on the parts list first, he was able to relate each component to its function and was created a better list of energy conversions. This shows that identifying components first allows students to think in terms of functions. Even though he only came up with one additional energy conversion, it was the more complex potential energy storage by the flywheel. This is definitely interesting because Richard was not sure about the nomenclature of the flywheel. He called it a 'spinning wheel'.

NOVICE - NO PART LIST:

The third interview was conducted with a novice. Rose is a Business major in her sophomore year. She was asked to come up with the energy conversions without a parts list. In summary, she:

1. Described the pig flashlight but missed some details.
2. Could recognize some energy conversions (3 out of 8)
3. Came up with one alternative for a specific function.

It was evident that her lack of understanding of scientific principles of energy and its conversions played a big part in her ability to understand the working of the flashlight. She was not able to recognize the energy conversions without significant prompting.

NOVICE - PART LIST:

Mary is an International Relations major in her sophomore year. She was asked to create the parts list before creating the energy conversion list. Her results show that she was able to,

1. Describe the pig flashlight, but missed some details.
2. Recognize five of the parts (Used her own nomenclature to describe them)
3. Identify five energy conversions.
4. Come up with two alternates for a specific function.

It was interesting to note that she was able to name most of the parts when she was asked to create the part list, even though she did not know the right names for them. This resulted in her recognizing more energy conversions than novice Rose. The results from this interview suggest that focusing on the parts list prompts the students to think about what the parts do, which in turn helps them develop a more detailed energy conversion list.

3.5 FINDINGS AND CONCLUSION

Each of these clinical interviews helped gain insights in the way students think and learn functional modeling when it comes to electromechanical device redesign. Some of the key conclusions drawn are:

1. The first and the most important finding is that the interviewees were able to identify functions even without the part list. The novices were not able to use the right nomenclature because of their limited knowledge. But they talked about the function using their own words. This is an important finding because this is the defining factor for whether a new tool has to be created or an existing tool can be modified to cater to their needs. It can be concluded that there is no a need to create a completely new tool for functional modeling. The energy flow that was used here was simple to understand and implement. This will be further developed and tested as a modified function structure focused only on the energy flow.
2. The differences between experts and novices were clearly recognized when identifying the energy conversions and alternate components. This shows that the level of scientific education affects the way students think about and learn functional modeling. In general, novice engineers and high school students will fall somewhere between the experts and the novices selected for this study. Since the novices struggled with the nomenclature, high schools will likely require instruction, through either reading materials or lectures, to learn standard nomenclature. Since the students will be working in teams and a common, correct nomenclature for components and energy transformations is important for both communicating effectively. This will help students who are not familiar with the energy and its conversions learn the content. This can also help in refreshing the knowledge of students who have some familiarity with the topic.
3. Listing the parts first appeared to improve the students' ability to think in terms of energy conversions irrespective of level of science education. This is a key finding because it is clear that part list creation does help in functional modeling.

Creating the parts list helped the participants think about what each part is doing and hence identify its function. In the context of reverse engineering, this step is part of the documentation generated during product disassembly.

4. During the interview, most of the time, the students had to be prompted to think about energy conversion and not components. There were a few times where even the experts slipped in and out of component recognition rather than function recognition. The novices did this more often. Hence, the student has to be constantly directed to focus on the energy flow in order for them not to slip into component recognition. This is important to avoid bias and fixation in solution generation. The new functional modeling tool should be developed with this in mind.

3.6 SUMMARY

In summary, the new functional tool to be developed should take into account that the students already think in terms of functions intuitively, but there needs to be a way to focus the their attention on the functions when they slip into component thinking. Also a new step in the curriculum to teach energy, energy transformations and its nomenclature should be added. This can either be done as a lecture, a reading assignment or a collaborative learning activity guided by the teacher.

CHAPTER 4
METHODOLOGY, EXPERIMENTATION AND RESULTS

4.1 INTRODUCTION

In this chapter, a new functional modeling technique is presented in detail. This new technique, called Energy Flow Diagram (EFD), was presented to a set of high school teachers for their feedback. Based on their feedback, changes were made and the modified EFD and lesson plans based on different time scales are presented here.

With the findings from the initial study, a new method of functional modeling was developed. The four main assumptions, informed by the initial study behind creating the new method, were:

1. Students already think in terms of functions intuitively, though they may not be aware of it.
2. The more knowledge and understanding the students have about energy and its transformations, the better they can model functionally using energy flow.
3. The students have to be constantly reminded to focus on abstraction.
4. The new method of functional modeling must be as simple as possible without losing the goals of functional modeling, which are problem decomposition and abstraction.

4.2 ENERGY FLOW DIAGRAM

With the above assumptions and requirements in mind, a new functional modeling technique was developed to be adopted in the *Engineer Your World* curriculum to aid high school students in creating functional models easily and intuitively. It is called the Energy Flow Diagram (EFD). The EFD is very similar to the function structure in the way that it tracks the flow of energy inside the system. The main difference between the EFD and Function Structures is the lack of signal and material flows in the EFD.

The removal of the interaction between the energy, material and signal flows reduces the complexity of the tool. Even with this much simpler version, the EFD maintains the goals of functional modeling in decomposing and abstracting the problem.

Each of the energy transformations can be achieved in a number of ways. This is how abstraction is achieved. Understanding and focusing on the basic energy conversions provides a basis developing innovative solutions that are driven by customer needs and constraints. Thus, though this tool may not be as thorough as the function structure, it is a good compromise that is more approachable by high school students. Moreover, the topic of energy and energy transformations is a standard for high school students in terms of scientific understanding. For example, students in the state of Texas are expected to already have a basic understanding of the subject according to the Texas Essential Knowledge and Skills for the high school course *Engineering Design and Problem Solving* (Texas Education Agency, 2010). This solves one of the main problems of the students' lack of expertise on the subject.

Another problem that identified during the interviews was the students who switched focus between the energy flow and components without realizing it. In order for them to stay focused on abstraction, a set of guidelines was developed for the students to follow while developing an EFD model. The guidelines are developed in the format of a step-by-step procedure to functionally model a product using EFD. It should also be noted that the students can use these guidelines as long as they want until they get a grasp of the abstraction process. Once they understand the idea of functional modeling, it is preferred that they not use the guidelines for future products. The guidelines are to be used as a prompting aid. Once the students are proficient in thinking functionally, they should be able to develop EFDs without guidelines.

4.2.1 EFD GUIDELINES

The EFD guidelines that were developed are as follows:

1) Start with input and output energy.

2) Identify the main energy conversions/transformations between input and output.
3) Identify the intermediate energy conversions. Make assumptions when necessary.
4) Can the system benefit from having a mechanical advantage, energy storage, or energy amplification (with an additional source)? Identify and include them.
5) Do the energy conversions need additional media to be transferred? Identify and include them.
6) Identify the energy losses.
7) Does the energy flow follow the laws of conservation of energy? If not, revise the model to ensure sure it does.
8) Revise the black box diagram for energy.

4.2.2 RATIONALE FOR THE GUIDELINES

The step-by-step guidelines are meant to be followed by students in order to develop the EFD. The guidelines need to be treated as a checklist in order to improve students' thoroughness with their functional thinking. It is perfectly fine if they do not have happening result for any given guideline. They should just move on to the next guideline. The guidelines were designed to keep them focused on the modeling process and abstraction. With each of these guidelines, it is highly recommended that the student sketch a diagram that can be expanded with each guideline. An example of EFD expansion at each guideline is shown in Appendix V. This can be done as long as the students are completely comfortable with the tool. Once they are comfortable with it, they do not have to expand the diagram at each step. They can directly go to developing the final EFD using the guidelines. Each of these guidelines is explained and justified in detail below.

1) Start with input and output energy.

For the EFD, since the signal and the material flows are removed, the need for creating the black box with them as inputs and outputs becomes unnecessary. The EFD only accounts for input and output energies. In the first step, the students identify the energies that the system takes in as input and gives out as output. This essentially is the black box. Once the students recognize the input and output energies, they have a firm understanding of the system they need to work with. This automatically creates the framework and the limits of the system, which is the purpose of the black box.

2) Identify the main energy conversions/transformations between the input and output.

This second guideline focuses students on the main energy conversion needed between the input and output energies. Usually there is more than one energy conversion between the input and the output, and collectively they are all arguably the main energy conversion. But the reason the word ‘main’ is used here is that the students are expected to slowly expand their horizon of thinking. In this stage, the EFD is expanded with additional blocks that are inserted between the input and output energy.

3) Identify the intermediate energy conversions. Make assumptions when necessary.

This is the guideline that is designed to push the students’ thinking a little further. Once they have decided on the 'obvious' energy transformations in the previous guideline, this guideline demands that they think in a more thorough and detailed manner to come up with additional energy conversions. It is perfectly okay if they do not have any additional energy conversion or if they already have recorded one in the previous guideline. The EFD expands again with these additional blocks of intermediate energy. This guideline was considered necessary because, during the clinical interviews, it was found that the students needed prompting occasionally in order to add the missed energy transformations. A two stage process will help them in thinking more thoroughly.

4) Can the system benefit from having a mechanical advantage, energy storage, or energy amplification? Identify and include them.

The term energy amplification is used here to indicate that in some instances, the system might need additional energy that may not be provided by the existing flow of energy. An external source of this additional energy must be included in the EFD. It must be made clear to the students that according to the laws of conservation of energy, the energy cannot be amplified without an external source (Appendix VII).

This is the first time the students are asked to look for specific types of energy conversions in the system. The key here is the possibility of innovation because the students might think there is a mechanical advantage between two energy transformations, only to find out after disassembly they do not have one. Now the student knows that the system could benefit from adding a mechanical advantage at this stage of energy conversion, and that becomes an improvement in the system is the most abstract way. How they implement the mechanical advantage is addressed later during concept generation. A disadvantage of this guideline is its complexity. The EFD could easily become very complex with this guideline. So time should be taken by the students to be thorough about it. Another major disadvantage is the familiarity with the terminology. It is not clear whether the students are familiar with the terminology of mechanical advantage, energy storage and energy amplification. If they are not, they students might get stuck at this stage. But this problem can be addressed supplemental teaching. The EFD is expected to expand considerably at this stage.

5) Do the energy conversions need additional media to be transferred? Identify and include them.

This guideline was designed to make the student think about the limitations of how and in what conditions a particular energy can be transferred or converted to another type of energy. They need to think about the medium the conversion needs in order to make the transfer and conversion happen. For example, sound energy needs air to transfer. It should also be stressed to the students that some of these energies also need to be transferred and not just transformed. Transfer of energy also provides abstraction that can later be used for innovation when generating concepts. The EFD will become even more complex at this phase with all the additional transfers and transformation media included.

Before this guideline, the students were generating or recognizing functions that they work with during concept generation. The guidelines from this point ensure what they have created is scientifically reasonable. In a way, the next three guidelines validates the EFD.

6) Identify the energy losses.

In this guideline, the students are made to think about the efficiency and inevitable energy losses. From the first guideline, they know they have limits on the type of input and output energies t. But not all the input energy converted to output energy. No system is 100% efficient. They are always losses. These losses occur during almost all the stages of energy transfer, energy transformation, and energy storage. Sometimes the losses are very small. These losses can be ignored. But any substantial loss needs to be recorded. Losses are represented using output arrows. Sometimes it can be hard to tell which energy is lost without deciding how the energy is converted. In other words, different components have different energy losses or at least different percentages of energy losses. This needs to be noted because this becomes an opportunity to redesign the system to be more efficient. In a scenario where the students do not know what energy is lost from the system, the teacher can ask them to make assumptions about how the problem might have been solved and then think about the energy losses.

7) Does the energy flow follow the laws of conservation of energy? If not, revise the model to ensure sure it does.

This is a vital step in the guideline. This guideline directs the student to consider feasibility when it comes to energy and its conversions. The basic definition of the law of conservation of energy says, 'Energy can neither be created nor destroyed. But it can be transformed from one type to another.' Knowing the inputs and outputs, the student already has a framework for expressing the law of the conservation of energy. The law simply states:

$$\text{Input energy} = \text{Output energy} + \text{Losses}$$

The students at this point need to make sure they are not creating any energy that cannot be part of the system. They need to make sure their losses obey the law of conservation of energy. The students can make the necessary modifications at this point to fit the law.

8) Revise the black box diagram for energy

Now with all modifications complete, the student can go back to the first step and rethink the energy inputs and the outputs and update the EFD accordingly. The students can go through the guidelines again in order to be more through. They can do it as many times as they want, modifying the EFD as they recognize and discover more. It is recommended that they review the guidelines at least twice before they finalize their EFD.

4.2.3 ADVANTAGES AND DISADVANTAGES

The major advantages and disadvantages of the EFD and its guidelines are discussed here in detail.

Advantages of EFD:

1. Simple and intuitive to use

One of the main goals of this research was to find a functional modeling method that is very easy and intuitive to use, and the EFD method meets both these criteria. The function structure is intuitive but too complex for high school students, so its implementation becomes difficult. The much simpler function tree lacks a clear structure, making it less intuitive to use. The EFD falls somewhere in the middle of a function structure and function tree in terms of simplicity. And it is definitely more intuitive than both of them. It has the advantages of both the tools and does not share the disadvantage of either of them.

2. Keeps the students focused

This advantage can be attributed to the guidelines developed. The guidelines define the teaching method as well. This is a teaching strategy decision. By using the guidelines as a form of checklist, the students focus on the task at hand. This also solves the problem of students switching between function and components without realizing it.

3. Less reliance on teacher involvement

Providing explicit guidelines allows students to develop their own EFD with minimal intervention from teachers. This is an advantage because inherently, functional modeling does not have a 'right answer' and when different teams work on the same functional model, they all develop EFDs that are different from each other. This can lead to a lot of confusion if the teacher is trying to teach the entire class, developing the EFD at the same time. This becomes worse if they are developing EFDs for different products. Thus, the guidelines can make the student independent of the teacher. The teacher may still use an example to walk them through the guidelines and show them the method.

4. Energy is an appropriate topic

The energy flow in a system is a vital chain of functions in terms of providing innovative solutions in the context of energy conservation. With the push by society for greater energy efficiency, focusing students on the energy flows in a system and redesigning the system to be more efficient is inherently interesting to everyone. This also helps them gain a firm grasp of different energies and their transformations, giving them a firm understanding of those particular science concepts.

5. Fits seamlessly in the existing curriculum

Though this method removes the need for teaching the black box model, other than that, it fits seamlessly into the existing curriculum. In fact it might take less time to teach students EFD than function structures. The students may need instruction in certain concepts before they can use EFD. But based on the TEKS, they are expected to have seen these concepts before. They can also be refreshed easily using supplemental lectures or study materials.

<u>Disadvantages of EFD:</u>

All functional modeling tools have their own disadvantages. For example, the main reason for developing EFD is the complexity of function structures and the less intuitive nature of function trees. EFD falls between them. So the disadvantages of the EFD could be compared to function structures and function trees. The four main disadvantages of the EFD are listed and discussed below.

i. No signal and material flows.

ii. Excluding black box diagram from the curriculum.

iii. Does not perform equally for all products, such as those with few energy transformations or significant material flows.

iv. Different EFD for different people.

Each of these is discussed below.

i. No signal and material flow

The main disadvantage of the EFD is the exclusion of signal and material flows in the system. The signal and material flows play an important role in many electromechanical systems. In the context of reverse engineering, the products we choose for teaching functional modeling always have some form of signal and/or material flow. Most of the products at least have an ON and OFF switch that provides an input signal. Though ON and OFF could be simple signals, some products use sensors to automate certain functions. Exclusion of such a function in a system removes possibilities for innovation. The same goes for material flows. Material flows play an important in many systems. By ignoring these flows, crucial innovation could be missed. This is by far the biggest disadvantage of the EFD method.

However, the EFD still achieves the fundamental goal of abstraction and innovation in concept generation better than the function trees. Though not representing as much detail as function structure, this tool is much simpler for the students to grasp. The tradeoff is between the simplicity of the tool and the thoroughness of the modeling.

ii. Excluding black box diagram from the curriculum

The function structure starts with the black box that includes the energies, signals and materials flowing into and out of the. This gives the designer an overall picture of the system its relationship to the user and the environment. The function structure provides the details of what happens inside the black box. The black box creates a strong framework to work with. With the EFD, since we have removed the signal and material flows, the black box became redundant because the first step of the EFD guideline was to map the input and output energies. This can be considered a black box with just the energy inputs and outputs.

The actual black box can be included in the lesson in order to make the students aware of the other inputs and outputs in the system. This might help them in realizing that energy is not the only type of input or output. This might increase the level of innovation in their solutions due to the added information. There could be confusion on the students' part about the energy carriers of signals. Often the energy carrier is ignored for a function structure, but the EFD may cause students to focus on these energy sources as well. This actual black box can be included based on the teacher's comfort on their students' ability to grasp the concept.

iii. Does not perform equally for all products

Another major drawback with this method of functional modeling is the inability of the EFD to perform equally on all products. Some products have many material flows or complex signal flows and very simple energy flows. Consider a coffee maker that also grinds the coffee beans. Here the material flow is clearly important. There are the coffee beans, water, filter, and cup as inputs, and ground coffee and the actual liquid coffee drink as outputs. There are six different material flows in the system. By completely ignoring this, the design loses its maximum innovation potential. The energy conversions themselves can be as few as two or three. Mapping only two or three functions might limit possibilities for innovation considerably.

iv. Different EFDs for different people

Though this is a common disadvantage of any functional modeling tool, it has to be recorded here as well. The EFD is no exception. The final EFD can be different for different designers. This might create some confusion among the students. It is essential that students understand that it is okay for there to be multiple answers for the same product. *In fact, this is where innovation happens, and this is an essential characteristic for any open-ended problem*. But the teacher is advised to create a reference EFD before introducing the activity. It should be noted that grading for this section should be based more on the overall quality of the EFD rather than comparing it with any particular 'right' answer.

4.3 EVALUATION BY HIGH SCHOOL TEACHERS

To validate the hypothesized advantages, the effectiveness of the EFD method was evaluated. The initial test population was the high school teachers who were learning reverse engineering for the first time. In many ways, teachers are the immediate customers of the method. If the EFD method appeals to the teachers and they recognize the advantages of using the EFD, then the tool can be considered ready for inclusion in in the high school curriculum.

The UTeach*Engineering* program provides a professional development course for high school teachers who teach the *EYW* curriculum. The teachers receive rigorous training on the curriculum and on problem-based learning strategies. They learn a functional modeling technique within the context of reverse engineering a consumer product. The EFD was introduced to the participants of this course during 2013 and feedback was collected.

The main goals of this testing were:

i. To get the feedback from the teachers on the simplicity and intuitiveness of using EFD

Even though this tool was designed to be simple and intuitive to use, validation by teachers was important for concluding that the EFD is indeed simpler and more intuitive to use than both function structures and function trees. This feedback is vital in order to understand whether the tool is ready students as well. The teachers can provide insights into whether the tool will fit the students' needs and abilities. It was very important that they find the tool simple and intuitive to use. It was important that they recognize the advantages of using this tool.

ii. To understand whether there may be any additional need for lectures to cover certain topics

Lectures or reading materials for refreshing basic energy and energy conversion topics were deliberately left out from the testing for two reasons. First, the teachers were expected to be familiar with this material. Second, even if some teachers were not familiar with the material, some crucial insights could be gained on what exactly needs to be included in the lectures or teaching materials. Feedback was also solicited about whether they think the students might need any additional materials to understand the method better and use the EFD more effectively.

iii. Introduce the product and get feedback

It is very important that the teachers find the product interesting, intuitive and easy to use when functionally modeling the device using EFD. For this study, only the opaque light was used. The EFD itself created only for the product before disassembly. This was done so that raw functional thinking can be captured without the influence of looking inside the product working. The initial study already reveals that the EFD is more detailed after disassembly.

iv. To determine if EFD fosters innovation

The final goal of the study was to determine if the EFD produced any innovative ideas from the teachers. They were simply asked to brainstorm components for each of the energy transformations inside the system. At this stage, the teachers were not exposed to any concept generation techniques. As it would take a lot more time to teach them concept generation and to allow them to develop and evaluate concepts, a simple lecture was created to discuss the idea of abstraction and the many possibilities of solving the problem. It was established that the more components they envisioned for each energy transformation, the higher their level of innovation was.

4.3.1 TEST PROCEDURE

A study was designed and implemented based on the goals discussed above. The following test procedure was created:

1. Pre-test (20 minutes)
2. Lecture (30 minutes)
3. EFD for the hand cranked flashlight using EFD guidelines (20 minutes)
4. Q&A (10 minutes)
5. Post questionnaire (20 minutes)

The timings for each of the step were strictly followed. The post questionnaire can be seen in the Appendix VI.

The pre-test was a simple test that was borrowed from the Citrus County (Florida) School District (n.d.) that was designed to test the basic understanding of energy and its transformations. This test was used to determine how much the teachers knew about energy and its transformations before they were introduced to the product and the EFD method.

The teachers were a mixed group. They were specialized in many different STEM subjects. They ranged from mathematics, chemistry, physics and even engineering. Another reason this test was used to was to identify any advantages for teachers who were teaching physics versus other subjects. It was expected that they were quite familiar with the different types of energies and its transformations. The test had 15 questions based on energy and its transformations. Twenty minutes were given for them to finish the test.

Once the test was completed, the lecture was given. The lecture was an hour long and was aided by a PowerPoint presentation. The hand cranked flashlight was introduced in the context of reverse engineering and functional modeling. The lecture had two examples. The first one was a hair dryer, and the second one is the flashlight. The hair dryer was used to teach them the idea of energy flow without using the guidelines. They were guided through the process in the format of the lecture in the most logical way. This was done to show them the intuitiveness and the simplicity of the tool. Once that was done, the guidelines were introduced, the hand cranked flashlights were handed out and the teachers were asked to develop an EFD using the guidelines. Twenty minutes were allotted for this exercise. They were allowed to discuss their work with their neighbors. This was done because the high school students themselves will be working in teams to solve the problem. Once they completed their EFDs, the lecture continued with the EFD developed by the researchers and the teachers were asked to compare their results with the results on the presentation.

This was followed by simple question/answer session where the teachers expressed their uncertainties and got further clarity on the tool. An interesting outcome from this session was that one of the teachers had a more detailed EFD than the one that was presented in the lecture. This validated the point that there are no right and wrong answers in the functional modeling technique. It also validates the thoroughness of the guidelines, which will be discussed in detail in the next section.

The final 20 minutes of the study were dedicated to the post questionnaire where the teachers were asked feedback on various aspects of the EFD evaluation. The questions were in the form of Likert scale ratings between 1-10 and questions that required their written feedback and suggestions.

4.3.2 FINDINGS

In general, the feedback from the teachers was supported the EFD. The findings are categorized by the goals and evaluated on how well they performed, capturing both positive and negative feedback.

1. Simplicity and Intuitiveness

The teachers found EFD much simpler and more intuitive to use than function structures. They thought the flow was simple without the interaction between the signals and materials present in the function structures. Most of the teachers felt positively about implementation of the EFD in the high school setting. They said that they believed that the high school students would find the tool much more simple and intuitive to use compared to function structures.

The teachers particularly liked the EFD guidelines that were provided. They thought the guidelines helped them focus on the method in a step-by-step manner. The simplicity of the tool was due in part to the guidelines. They felt the guidelines helped them to identify more details on the product functions.

The teachers found a problem in the introduction of the guidelines on one slide. This much detail on one slide overwhelmed them and they said the high school students would feel the same way. This might not be an intuitive way of introducing the EFD for the first time. Another more intuitive way that is not so intimidating must be used.

The guideline about the medium of transfer and conversion also confused the teachers. This might be because the guidelines suddenly jump to materials instead of dealing with energies. It is understandable that the teachers got confused about this specific guideline. It was a break in the pattern of thinking. Though it is important to think about the medium of transfer and energy transformation, it was found that this guideline did not fit the EFD and compromises the simplicity of the tool. For these reasons, this guideline will be removed.

2. Need for additional knowledge transfer

The post questionnaire reveals that the guidelines were easy to understand and implement. The teachers thought the example of the hair dryer used before they started working on the hand cranked flashlight was very helpful in understanding what they were required to do. One problem pointed out during the Q&A section was their lack of understanding of some the terminology used in the guideline about mechanical advantage, energy amplification and energy storage in the EFD. Though they understood energy amplification and energy storage, the mechanical advantage was not understood by them. They asserted that the high school students would not understand them either. They also said that the high school students might find it difficult to understand the concepts of energy amplification and energy storage as well. And they might need to brush up on the laws of conservation of energy as well. Lectures or reading materials must be provided in order to teach those concepts.

3. Hand Cranked Flashlight

The teachers were strongly in favor of the hand cranked flashlight to continue as the product of choice to reverse engineer and develop an EFD for. They were surprised by the compactness of the device compared to the number of energy conversions. They asserted that this will increase the curiosity and interest of the high school students. They liked the variety of energy conversions in the device as well. This helps the students think in terms of the functions of the device. They liked the aesthetics of the as well. This specific product was designed in the shape of a pig. They thought the product would be fascinating for all genders.

4. Concept Generation

As part of the lecture, when the teachers compared their finished EFD with the one provided on the lecture slide, the teachers showed their ability to innovate by identifying additional functions that were not captured by the researchers. This validated the point that the EFD allows innovation and creativity even when being used for the first time.

4.3.3 CHANGES IN EFD GUIDELINES BASED ON TEACHERS FEEDBACK

With the feedback gained from the teachers, certain changes were made to the EFD guidelines.

1. *Explain basic concepts of energy and its conversion along with mechanical advantage, energy storage and energy amplification,*

One of the most common complaints from the EFD test with the high school teachers was that they were not very familiar with the concepts of mechanical advantage, energy storage and energy amplification. Though they were able to understand what energy storage meant, they found it difficult to understand what energy amplification (with an external source) and mechanical advantage means. This feedback was addressed by explaining these concepts in the lecture clearly with examples. The teachers indicated that it would be beneficial to include the laws of conservation of energy in the concepts covered in the lecture as well. This will aid them in refreshing their memory on these concept, and will facilitate efficient usage of the EFD by the students. If the students are already familiar with the concepts of energy, energy types, energy transformations, law of conservation of energy, mechanical advantage, energy storage and energy amplification, the teacher may skip this part of the lecture.

2. *Removal of the medium of flow guideline*

This guideline was confusing to the high school teachers. This is because before this point, the teachers were set up to think in terms of energy alone and suddenly there is a guideline that forces them to think about the material or the medium, which is not an energy. This was pointed out by several teachers as something that would confuse the students. Based on this feedback, the guideline was taken out of the list. It should be noted that the removal of this specific guideline does not affect the EFD and its advantage of abstraction. Moreover, the medium of flow is more of a limitation of the energy type and its transfer rather than an abstraction.

3. *EFD guidelines handout*

One \criticism was the introduction of all of the EFD guidelines in a single lecture slide, which was overwhelming for the teachers. Some of them suggested that the guidelines be revealed one by one. The initial plan was to give out the guidelines to the students in the form of a handout. But instead of just having all the guidelines one after another, a graphical representation of what the EFD looks like at each stage was inserted between the guidelines. This gives a more graphical reference for the students.

CHAPTER 5
FINAL TESTING AND RESULTS

5.1 FINAL EXPERIMENT DEVELOPMENT

With the initial test with the high school teachers, three main changes were made to the new EFD module.

1. A lecture on the basics of different types of energy and its transformations, energy amplification, storage and mechanical advantage was provided.
2. The medium of flow guideline was removed from the EFD guidelines.
3. A handout of the EFD guidelines, graphically representing every guideline and how it will look when developing them, was handed to the students before they created the EFD for the hand cranked flashlight.

The next step was to evaluate the modified EFD method with undergraduate students. This test population more closely resembles the target audience for the tool. The main goals of the study were:

1. Implement the EFD with novice engineers to determine if the EFD is easy and intuitive to use.
2. Evaluate the effectiveness of handouts and lectures presented.
3. Identify any differences in the usage of EFD based on gender, level of education and major.

5.1.1 PARTICIPANTS

The study was conducted with a set of novice engineers who had not been exposed to design methodology. A set of 67 students from The University of Texas at Austin was selected. The participants were from a general engineering class that can be taken by anyone from any major and year at the undergraduate level. The general topic of the class 'how things work'. As shown in Figure 4, there were 39 freshmen, 14 sophomores, 6 juniors, and 2 seniors. As shown in Figure 5, the participants included 56 males and 11 females.

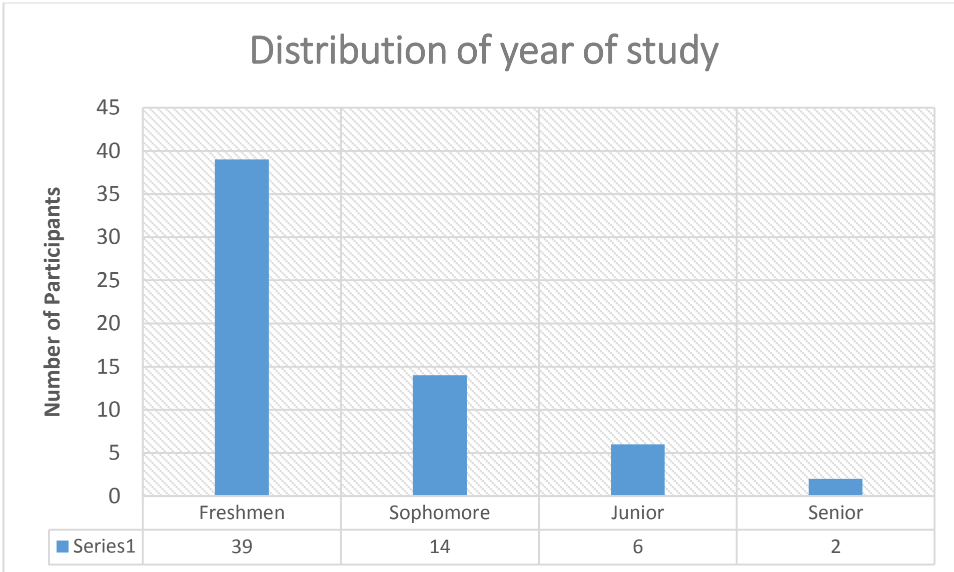


Figure 6: Distribution of year of study of the participants

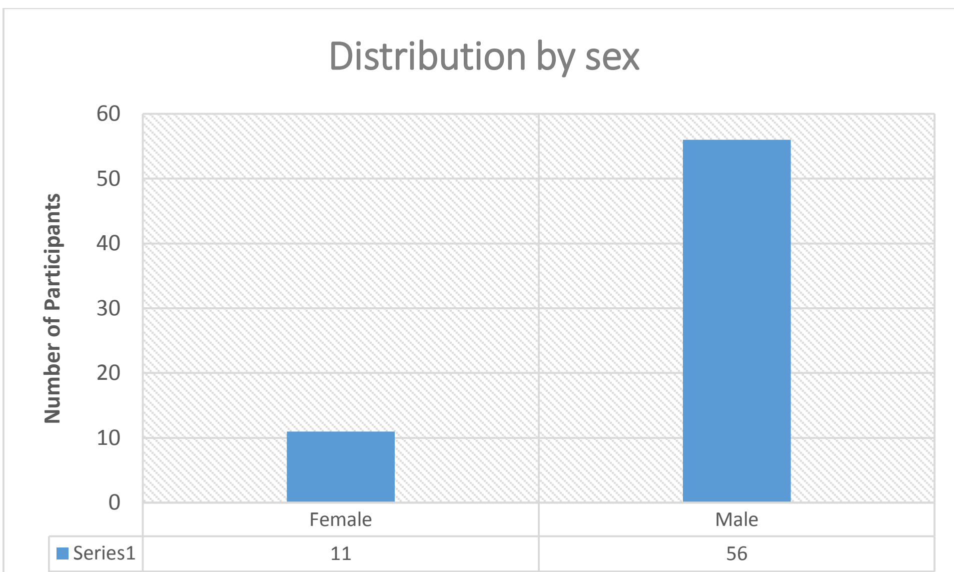


Figure 7: Distribution of the participants based on sex

Since this study falls under the category of human subject research, an IRB application was filed and the study was designated as an IRB exempt study. The study number is IRB Protocol 2014-10-0033.

5.1.2 TESTING PROCEDURE – PRE/POST TEST

The main method of collecting the data was via a pre and post-test. This methodology for measuring the effectiveness was implemented because it can provide a direct value for the level of learning the students have attained through the lecture and the new EFD.

A new pre-and post-test was developed (Appendix VII). Both tests were exactly the same. The pre-test was taken by the participants before the lecture and the post-test was taken after the lecture. The EFD handout was not provided for the pre-test, but was provided for the post-test. The hand cranked flashlight was shown to them for both tests.

The participants were first given 20 minutes to take the pre-test. A 30-minute lecture was presented on the different energy topics discussed earlier. Following this, the participants were given the EFD guidelines handout and were given 20 minutes to complete the post-test. The total time for the experiment was 70 minutes.

5.1.2.1 Pre/Post-test:

The pre and post-test were designed to determine if the lecture and the EFD guidelines made any difference in the participants' level of learning the EFD tool as a functional modeling technique. The following aspects of the ERD tool were evaluated:

1. Identifying input and output energy of a system.
2. Identifying energy transformations in a system
3. Identifying energy losses in a system
4. Identifying products based on functions
5. Identifying components based on functions
6. Applying functional modeling to the hand cranked flashlight

5.1.2.2 Rationale behind the test questions:

The pre and post-test has a total of nine questions based on the six criteria to be tested. The most important of these was the development of the functional diagram for the hand cranked flashlight. This was a direct test addressing both the EFD as well as the product used. This also holds the most weight in the test with 30 points. This question was asked last because the students were first made to think about all the different sub-functions in the other previous questions based on criteria 1-5 above. This made the students consider all the flows that they might otherwise miss. This was more relevant in the pre-test when the handout was not given. In order to be fair with respect to time, the same order was followed in the post-test. But this was not mentioned to the students. They were allowed to answer the questions in any order they wanted.

For the first criterion, the students were asked to identify the inputs and outputs for two products. The two products used in the test were a battery operated hand held flashlight and a vacuum cleaner. This also is the first guideline of the EFD, which is to identify the input and output energy of a product. As discussed in chapter 4, the first guideline of the EFD is essentially a representation of the black box. From the functional modeling perspective, it is very important for the students to identify the inputs and the outputs first. They were given five spaces for five inputs and five outputs. This was done in order for them to think in depth about all the inputs and outputs. This question provided valuable insights into the effectiveness of the discussion on different forms of energies in helping the students identify input and output energies of the product.

For the second criterion, the students were asked to identify the intermediate energy transformation that occurs in the flashlight and the vacuum cleaner. This is a merging of the second, third and fourth guidelines. They were asked to identify the main energy conversion, intermediate energy conversions and the inclusion of energy storage, mechanical advantage and energy amplification in the device. This was done in order to help the students think inside the 'black box'. This is when they start creating the internal functions of the product. Though the example products were simple enough, the students were still expected to decide what happens inside the system with just the help of the inputs and outputs that they identified for the previous question. This question will reveal the differences the lecture on energy transformations made in their ability to think functionally.

For the third criterion, the students were asked to identify the energy losses in the products based on the internal energy transformations. This is based on the fifth and sixth guidelines of the EFD. This question revealed their understanding of these concepts based on the lectures even if they only needed a refresher on these concepts.

For the fourth and fifth criteria, a part of a functional sequence was presented. The participants were asked to identify three products for the fourth criteria and three components for the fifth criteria that fulfill the energy flow. This was done in order to test their ability to think functionally. This question is very important in order to validate that the EFD is used as an abstraction and concept generation tool. By asking these questions, the participants were made to think of a functional sequence first and then think about the different products and components that embody these functional sequences. The results from this question will validate the EFD for its abstraction.

5.1.2.3 Lecture and Handout:

The lecture was designed to cover the following topics based on the first study with the high school teachers;

1. Basic energy concepts
   i) Energy state
   ii) Energy conversion
   iii) Energy loss
   iv) Conservation of energy
   v) Mechanical advantage
   vi) Amplification
   vii) Energy storage
2. What is functional modeling?
3. What is EFD?
4. Example product as part of the lecture to explain energy flow - hair dryer.
5. Present EFD guidelines.

Suggested lecture slides on these topics are attached in the Appendix VIII. The lecture was designed as a both a new topic discussion as well as a refresher of concepts that they have already learned in middle and high school.

The EFD guideline handout was designed keeping in mind that the students would benefit from having a handout that they can refer to at any time during the creation of the EFD for any product. The handout contains the six EFD guidelines. Each of the guidelines is also graphically represented in the handout for the students to get an idea of how the EFD can be represented for a given product. The sample EFD guideline is attached in the Appendix IX.

5.2 ADMINISTRATION

The test administered as described previously. The timing of the evaluation was:

IRB explanation - 10 minutes

Pre-test - 20 minutes

Lecture - 30 minutes

Post-test - 20 minutes

5.2.1 CHALLENGES

Some of the challenges faced when administering the study are presented in this section. These challenges influenced the data collected and the way the data was analyzed. These challenges described here along with how they were addressed and how they affected the data collection and analysis procedure.

1. *Students coming in late*

The first challenge was that some students came in late, well after the pre-test started. Since this study was conducted in a classroom, it was anticipated that some students would come in late. To avoid conflicts in the data collected, late-arriving students were allowed to take the test and attend the lecture, but the data collected were not used for the analysis of the study. Only one student was late for the class. The student completely missed the explanation of the IRB and was five minutes late for the pre-test. The student was not allowed to take the pre-test, but was allowed to sit through the lecture and take the post-test. The test was disregarded for this student for the data analysis.

2. *Students not interested or focused on the test*

Some students can be very uninterested in taking the test. They may not be entirely paying attention to the test. This cannot be avoided. In order to interest them in the test, the students were first motivated to take the test seriously. It was announced that an incentive of a hand cranked flashlight would be given to everyone who answered all the questions in both the pre and post-test. They were also motivated to take the study seriously for altruistic reasons since the data that they provide would be used to develop the EFD tool further to help high school students and novice engineers become more passionate about science and engineering. It was expected that some of the students would be motivated by this.

3. *Students not bothering to complete the test in its entirety*

In spite of the incentives and the motivation, some students still did not complete the tests. This could be for different reasons. One possible reason is that they genuinely did not know the answers to the questions and left them blank. Another reason may be that they were not motivated to answer the questions. This was a tricky challenge. This was partially solved by creating a grading rubric that calls for a judgment on whether the student genuinely tried to answer the questions or not. Some of the test sheets contained notes like 'I don't know' or 'I do not understand the question' or with a simple question mark '?'. These were taken as an indication that the students did read through the questions and did not know how to answer them. Another criterion used to distinguish the tests that were not genuine were those that were filled for the first few questions, with the rest completely disregarded. These tests were discarded. Whereas the ones that answered the first and last few questions were kept even though they did not have any markings on the questions that they left blank. The assumption behind it is that the student read through the entire test and chose to answer the questions that they knew how to answer. This was considered a genuine attempt at the test. Any test that was left blank after the first few questions was graded to see if the answers were relevant and of high caliber. If not, they were discarded. Five tests were discarded in this manner.

4. *Students not completing the post-test and turning it in*

Since the post-test was the last task in the study, it is suspected that some of the students just wanted to finish the test as soon as possible. Two of the tests were discarded because they gave in an incomplete post-test. Both of them answered the first few questions and they completely left out the other ones with no indication that they went through those.

With all the discarded tests, the sample size became 67, the breakdown of which is discussed in the previous section.

5.2.2 GRADING

After the data were collected, a grading rubric was created in order to evaluate the tests. The total possible points was 94. The most points were allocated to the final question of creating an EFD for the hand cranked flashlight. The final question alone was worth 30 points. In order to grade that, a separate grading standard was set up. This was necessary in order to make sure the points were awarded according to importance. The breakdown of the 30 points is shown in Table 3 below.

Points	Reason
5	Flow arrows used
2	For each energy captured in the flow
2	For every mechanical advantage, energy storage and energy amplification identified
2	For each of the losses identified

Table 3: Grading rubric

Using the above rubric, each of the EFDs created was graded. Care was taken to give full credit to the energy, mechanical advantage, energy amplification, energy storage and energy losses that were all correct from a nomenclature aspect. If the participant represented an item but used their own language, partial credits were given. The partial credits were 0.5, 1 and 1.5.

For the first question, where the students were asked to identify the inputs and outputs of the system, 1 point was awarded for each of the energies they captured, both input and output. Human energy as an input warranted an additional point if they identified it. This was done because human energy is only relevant in product development and to think about it from that perspective, a bonus was awarded.

For the second question, 1 point was awarded for each of the intermediate energies identified. The intermediate energies could be anything ranging from the major energy transformation, mechanical advantage, and energy storage and energy amplification. Since there were a lot of energy flows inside the given device, 1 point per identification was enough.

For the third question, 2 points were given for each of the losses that they identified. This question warranted 2 points each because, in order to know the energy losses, the students should also think about the components that are used to achieve a specific function and then think about the energy that is lost due to that component. Partial credits were given when the participants described the loss without using the right nomenclature.

For the fourth and fifth question, 3 points were awarded for each of the products and components that they identified. Partial credits of 1.5 were given when the participants did not use the actual nomenclature but attempted to describe in their own words.

5.3 RESULTS

Every question's average score increased from the pre-test to the post-test. The graphical representation of the results is shown in Figure 6.

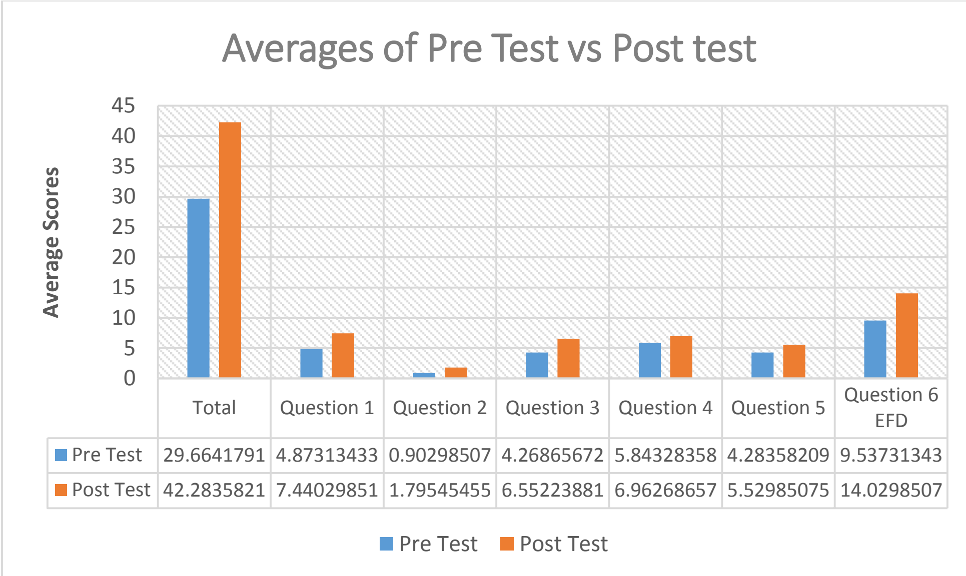


Figure 8: Graphical Summary of Results

The average total for the pre-test was 29.9 and for the post-test was 42.2, There was an average increase of 12.3 points. Of the average increase of 12.3 points, 4.5 points comes from the increase in the EFD created for the hand cranked flashlight. The difference in the average for the first question was 2.54. For the second question it was 0.9 which was also the lowest increase in average. The third, fourth and fifth questions had an increase in average of 2.25, 1.16 and 1.23, respectively.

The increase in the post-test average between the male and female participants differed only by 1.3 points. The male increase in overall average was 12.4 and the female increase in overall average was 13.7. But it should be noted that the average for the pre-test for the males and females are 31 and 22.6 respectively. A similar trend is seen for the post-test are, 43.4 and 36.3 respectively. It should also be noted that there were only 11 female participants compared to the 56 male participants.

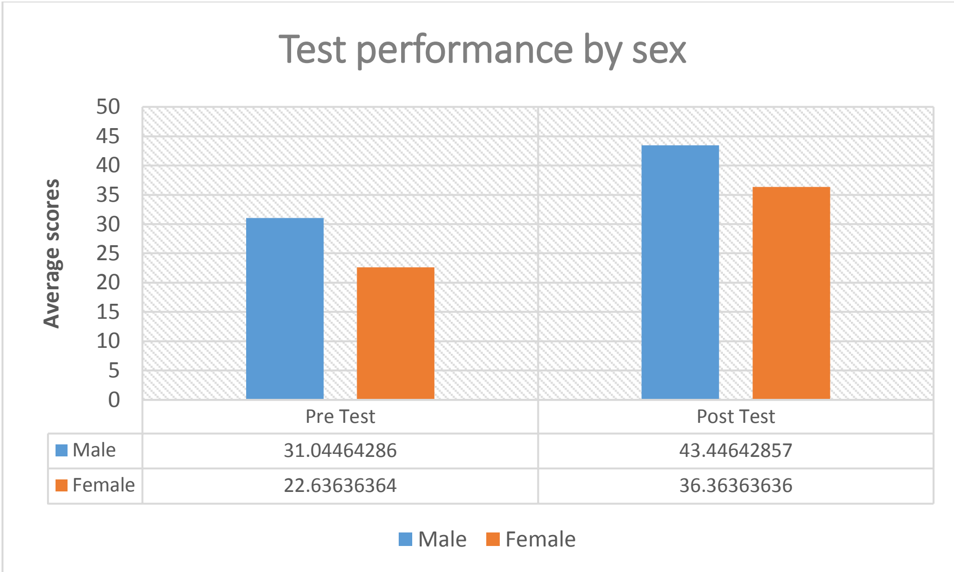


Figure 9: Performance based on sex

Looking at the trend in different levels of education, seniors had the highest increase in the average with 19 points. Juniors came second with an increase of 14.8 points in the average. Freshmen, who were the majority of the sample, came in third with an increase of 12.7 in their average. The sophomores came last with an increase of 11.9 in their average. It should be noted that there were only 2 seniors compared to the 39 freshmen in the sample. There were 14 sophomores and 6 juniors. Six of the participants did not provide their year of school.

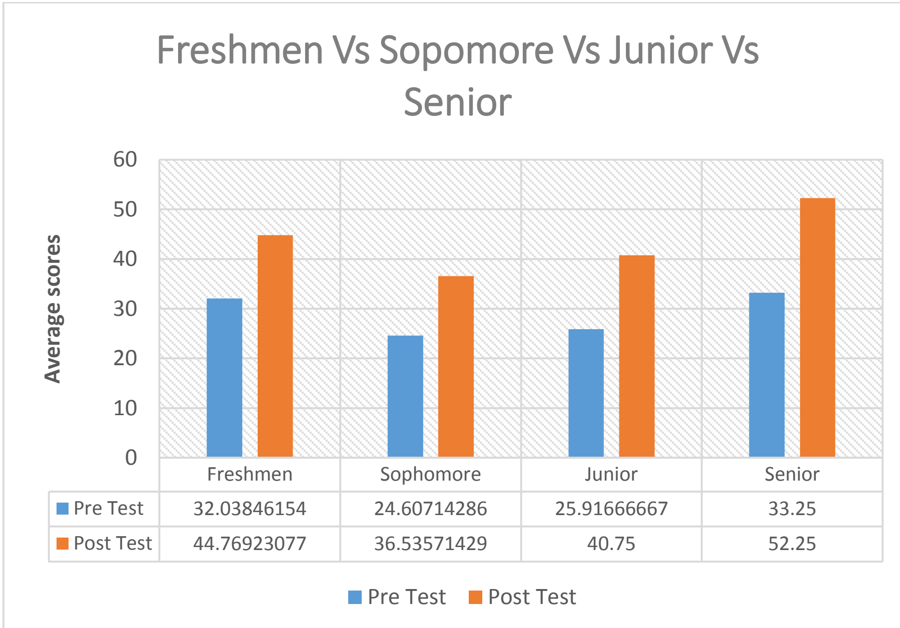


Figure 10: Performance based on year of study

Dividing the sample by majors, it was found that the liberal arts students got the highest increase in average of 15.3 with engineering majors coming in second at 12 and the science majors at 11.2. There were 24 engineering students, 18 science majors and 18 liberal arts students and 3 undeclared and 4 who did not provide a major.

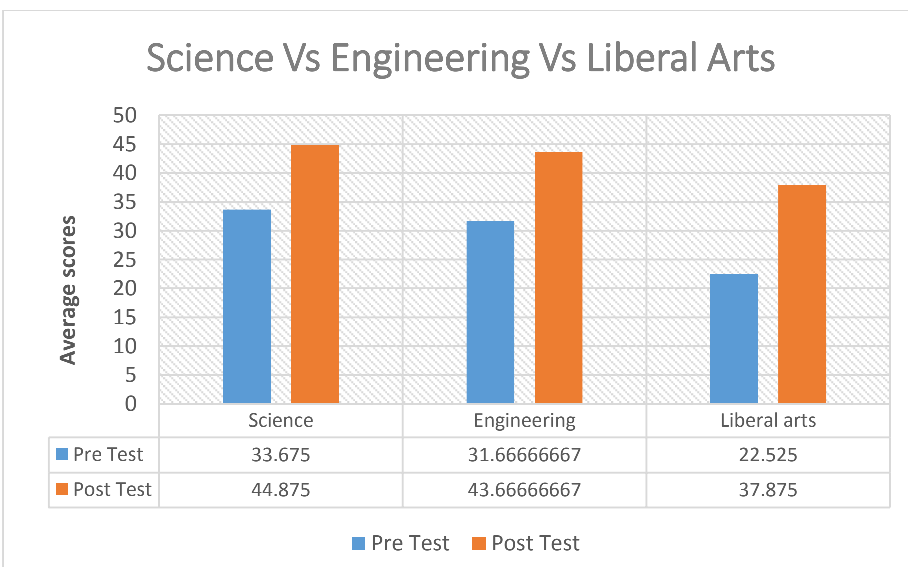


Figure 11: Performance based on major

From the individual perspective, the highest scores were 56 and 67 for the pre- and post-test, respectively. A freshmen in Mechanical Engineering received these scores. The lowest scores were 1 and 20 for the pre and post-test, respectively. A female Electrical Engineering freshmen received these scores. The biggest increase in the total score between the pre and post-test was 33, with a pre-test score of 20 and post-test score of 53, by a male junior in Liberal Arts. The lowest increase in score was 1.5 by an Engineering student. There were two tests that had a higher pre-test score compared to the post-test. The difference was the same in both of them, a negative difference of 5.5.

5.4 DISCUSSION

From the results, there are some interesting conclusions that can be drawn. There were some possible justifications for certain results and what can be done differently.

Some of the interesting conclusions are:

1. *EFD works - validated*

The most important finding from the final study was that the EFD method works. There was an increase in the scores of the participants from the pre-test and to the post-test. Of the 67 participants, 65 or 97% of them scored more in the post-test compared to the pre-test. With an average increase in score of 12.3 points, it can asserted that the EFD method of functional modeling and the accompanying lecture help the students develop a functional model of a given product effectively.

A simple matched sample t-test was performed and the value of t was computer to be -6.57 with a corresponding p-value less than 0.0001, which is much less than 0.05. This provides strong evidence against null hypothesis and that the results are statistically significant. There was a statistically significant increase in the performance of the participants on the post-test compared to the pre-test. This strongly supports the EFD method of functional modeling. The standard deviation of the pre-test was 11.8 and the standard deviation of the post-test was 10.3.

There are two things that stand out from this evaluation. First, the sixth question on creating an EFD for the hand cranked flashlight had an average the pre-test score of 9.5 out of 30 possible points and an average post-test score of 14 out of 30. With an average increase of 4.5 points, which is a 50% increase in the scores, it is clear that the EFD handout and the lecture substantially helped the students create an improved EFD. One of the most interesting findings on the EFD was that some of the participants developed an EFD diagram on the pre-test that closely resembled the EFD provided on the handout. This shows that the EFD is very intuitive to use. With the aid of the lecture and the handout, the students were able to fine tune their EFDs and use the correct nomenclature and flow, and consider other sub-functions like mechanical advantage, energy storage and energy amplification.

The second interesting finding from the study was the results of questions four and five. Those two questions were asked for different products and components for part of the EFD given. The average scores for the fourth question were 5.8 out of 9 and 6.9 out of 9 for the pre and post-test, respectively, with an average increase of 1.16. For the fifth question the averages were 4.2 and 5.5, with an average increase of 1.3. Due to the short time between the pre and post-test, this increase in 13% can be attributed to the lectures. The EFD itself, though it allows abstraction for innovation, does not directly show what other components can be used for a given function. For this study, the time spent on the energy and its transformation took roughly 15 minutes. That is a very short time to spend on a topic like energy and its transformations, which by itself could take three or four lectures to cover the subject more thoroughly.

2. Liberal arts vs Science vs Engineering

A particularly noticeable feature of the results is the difference in gains between the Liberal Arts and the Science and Engineering students. It is noteworthy that the Liberal Arts students, who more accurately represent an average high school student's understanding of STEM subjects, scored higher than both the Engineering and the Science majors. The difference in the averages between the Science and Engineering majors versus the non-science majors was 3.7. The average of the Science majors was

11.6 and that of the non-science majors was 15.3. While the increase in the average was higher, the actual average of the total was different. The Science majors simply scored more in both the pre- and post-test than the non-science majors. The average scores of the Science majors for the pre- and post-test were 33.6 and 44.8, respectively. The average score for the Engineering majors were 31.6 and 43.6, respectively. But for the non-science majors, the averages were lower at 22.5 and 37.8, respectively. From the results it can be inferred that the non-science majors were the ones that absorbed the most from the lecture and the handout.

A t-test between Science and Engineering majors was conducted with a t-test result of 0.276 and corresponding p-value of 0.78. This shows that the difference in results were not statistically significant. A t-test conducted between Engineering and Liberal Arts students shows that there was low level of significance between the both with a t-test value of 1.73 and p-value of 0.091. Note that the average increase between the pre and post-test of the Liberal Arts students was higher compared to Science and Engineering students, as discussed above.

3. *Male vs Female*

Another conclusion that can be drawn from the results is that there was no significant difference in the averages between the male and female participants. The male students scored an average of 12.4 and the female students an average of 13.7. Though there is a slight difference in the scores, this could be attributed the larger sample size of the male students. 83% of the participants were male. This provides a very good explanation of why the average is slightly less than the female students. This also indicates that the hand cranked flashlight activity is an equally attractive product choice for both the male and female students to be used by the UTeach*Engineering* program when teaching EFD as the functional modeling method.

Conducting a t-test, the value of t was found to be 2.13, with the corresponding p-value of 0.037, which shows that the results are not a statistically significant difference in the performance of the male and female students. This is the evidence that the EFD and the product used are not affected by the student's gender. The standard deviation for the male participants was 10 and the standard deviation for the female participants was 10.3.

4. *Year of education vs score*

Another finding from the study was that there was no significant difference in the averages of the freshmen when compared to juniors and seniors. Though the difference in the increase of average is 3.15, the juniors and the seniors comprise only 11% of the sample, compared to 58% of the sample being freshmen. Thus, the difference in the increases of their averages is not as significant. To put it into perspective, the freshmen got an increase in average of 12.7 between the pre- and post-test while the increase in the average for the juniors and seniors was 15.8. But the small sample size of the juniors and seniors makes absolute inference hard. The score is not significant based on the sample size, but if there were a bigger sample size, the difference might be more significant. In order to draw a conclusion, the scores of the sophomores were taken analyzed. The sophomores had an average increase of 11.9, which was 0.8 points less than the freshmen. Also, only 20% of the sample was sophomores compared to the 58% freshmen. This sheds some light onto the results of the juniors. The data show that the freshmen performed slightly better than the sophomores considering the sample size. Extrapolating that to the juniors and seniors, who scored higher with a much smaller sample size, it can be interpreted that the average performance was the same across all years of education.

A t-test conducted between the freshmen and sophomore participants' scores shows a t value of 2.72 with a corresponding p-value of 0.009, which is a strong evidence that there is a significant statistical difference in their performance. The freshmen performed better than the sophomores. A t-test performed between the sophomores and the juniors shows the t-test value of 0.826 with a corresponding p-value of 0.42, which shows no statistical significance between them. The performance of the sophomores and the juniors was the same. With the sample size of seniors being too low, a t-test was not performed on them. The overall summary shows that there was a significant difference in performance between the freshmen vs sophomores and juniors.

The study definitely shows that the implementation of EFD as a functional modeling tool will help students perform functional modeling in an effective way. Based on the results, lesson plans were developed and presented in the next section as suggested lesson plans for the *Engineer Your World* curriculum.

5.5 EFD SUGGESTED LESSON PLAN

The complete lesson plan for the EFD consists of the following,

1. Lecture/Presentation
2. EFD Guidelines handout
3. Teacher's handbook for EFD

Each section is explained here.

1. Lecture/Presentation

This is a suggested presentation that can be used by the teachers. It is suggested because this is only from the perspective of what the students need to know before they start their functional modeling. The teachers who actually work with the students know more about what the students know and do not know. According to the TEKS, the students are supposed to have a grasp on energy and its transformations. The most essential part of the /lecture is to solve an example problem with the students using the guidelines provided. The topics covered in the presentation are listed below:

1. Basic energy concepts
    - i) Energy state
    - ii) Energy conversion
    - iii) Energy loss
    - iv) Conservation of energy
    - v) Mechanical advantage
    - vi) Amplification
    - vii) Energy storages
2. What is functional modeling?

3. What is EFD?
4. Example product as part of the lecture to explain energy flow
5. EFD Guidelines
6. Exercise with a product and EFD guidelines handout before disassembly
7. Exercise with a product and EFD guidelines handout after disassembly
8. Q&A

The first topic of basic energy concepts presented here was taken from the terminology used in the guidelines, which plays an important role in effective usage of the guidelines to develop the EFD. A firm understanding of these concepts is necessary for the students to understand and use the guidelines. This section is optional, and there is a lot of flexibility for this section. If the students already have a firm grasp on all the subtopics listed there, this part can be skipped during the lecture. If the students are unfamiliar with certain topics, however, it is recommended that the teacher teach the topic in detail until the students have a firmer grasp of the concept. The lecture is flexible for the teacher to add any specific topics that they feel that the students need to know before using the guidelines. This will aid them in understanding and creating the EFD.

The second topic of functional modeling emphasizes the purposes of functional modeling and its importance. There are two main points that the students need to understand. They are functional modeling's ability to decompose the problem and to abstract the problem in order to generate more innovative solutions during concept generation. This allows them to see the importance of functional modeling practically when they are developing the concepts in the next stage. The students can also be made aware of the fact that there are multiple ways of functional modeling and that they are going to learn only one method.

The third topic is the first time the students are introduced to the Energy Flow Diagram (EFD). It is important that they understand how the EFD achieves both the goals of functional modeling. It is important to show them, through the example in the next stage, how EFD decomposes and abstracts the problem.

Next, an example product is chosen for explaining the idea of abstraction. The product suggested here is the hair dryer. The students have to be walked through the abstraction process before the EFD guidelines are given out. The most important reason for giving the lecture is to allow the students to see the intuitive and logical nature of the EFD and understand its usefulness. Once the EFD is completed for the hair dryer, the students can be encouraged to brainstorm other components that can achieve the same function. This will give them a strong grasp of the basics of functional modeling.

Once the students are walked through an example product as part of the lecture, the guidelines can be introduced and the guidelines handout can be distributed. The teacher may even walk the students through the example problem to show how the guidelines logically fit what they have already done, and even improve upon the existing model. The students can now look through the handout and clarify any questions that they might have.

Once the EFD guidelines are given out, an example problem can be given out for them to solve. The product that is recommended here is the hand cranked flashlight because of its advantages in terms of the number of energy conversions. The students can use the guidelines handout provided and in their own notebook draw out the EFD step by step. They can be allowed to work in teams where they can discuss the energy flow inside the device while they develop the EFD. Once they are done, the students can now use the transparent flashlight to look into the device to see the actual components and modify their predicted EFD using the guidelines for the actual EFD. Once they have completed their EFDs, the teacher can ask the students to exchange their EFDs to compare them, and then lead a discussion on the differences between the diagrams.

The final part of the lecture involves the students asking questions about the topics covered. The teacher can answer the questions about everything covered in the class to provide clarity. That will be the end of the lecture. Once the lecture is completed, the students can go back to the reverse engineering product that they selected in order to model their product using EFD. This paves way for the next phase of concept generation.

2. *EFD Guidelines handout:*

This is the handout given to the students once the example product has been solved during the lecture. This handout shows the guidelines with a visual flow diagram that gives a general representation of how the energy flows. It should be made clear to the students that the visual representation of the EFD is just that: a visual representation. It is not an expectation of the way that every EFD should look. The students can keep this with them. It is likely that students will need to refer to it when they are working with their products.

3. *Teachers' handout*

The teachers' handout is only for the teachers. It goes into detail on every topic covered in the presentation with more examples and sample EFDs. This is used as reference material for teachers who are not very familiar with teaching functional modeling. They can always refer to this document, which will answer most of their questions. It also comes with suggestions on how to implement the EFD, as well as warnings, tips and ways to answer possible tricky questions from the students.

5.5.1 TIME SCALE

The total time needed for implementation of the EFD can vary depending on the choices that the teacher makes and the time the students take to complete the tasks. Two lesson plans that are two ends of the spectrum in terms of the minimum and maximum time they can take to teach EFD are shown below. The first one was designed for the minimum time that has to be spent for effective learning of EFD and the second one is the time scale for the most comprehensive teaching of the EFD. Both of these lesson plans are based on the standard lesson plan that was described in the previous section.

1. *Effective lesson plan (90 minutes)*

For the minimum time scale to be implemented, it is necessary that the students are already familiar with the topic of energy and its transformations along with the concepts of mechanical advantage, energy storage, energy amplification and the law of conservation of energy. This lesson plan must not be implemented without the students having a firm grasp on those topics. The lesson plan and the time allotted for each section are given below.

1. What is functional modeling? - 15 minutes
2. What is EFD? - 15 minutes
3. EFD guidelines? - 15 minutes
4. Exercise with a product and EFD guidelines handout? - 30 minutes
5. Q&A - 15 minutes

The example problem to illustrate the intuitiveness of the EFD using the hair dryer is also removed from the lesson plan. By removing both these topics, the minimum time it takes to effectively teach the EFD is about 90 minutes. Again, this is only the rough estimate of the time. Typically the teachers can take two class periods to complete the lecture.

It should be noted that only the hair dryer example was removed from the lecture. The hand cranked flashlight exercise is kept intact because it is highly important that the students learn the functional modeling technique in a hands-on manner.

2. Comprehensive lesson plan (4 hours approx.)

This lesson plan can be used for teachers who have more time. If the teachers have ample time that they can spend on teaching functional modeling, this lesson plan can be used. The topics and the time allotted for each section are shown below.

1. Basic energy concepts - 90 minutes
    - i) System
    - ii) Subsystem
    - iii) System boundaries
    - iv) Energy
    - v) Energy state
    - vi) Energy conversion
    - vii) Energy loss

viii) Conservation of energy

ix) Energy flow

x) Input and output

xi) Mechanical advantage

xii) Amplification

xiii) Energy storage

2. What is functional modeling? - 15 minutes
3. Function structures and function trees - 20 minutes
4. What is EFD? - 15 minutes
5. Two example products as part of the lecture to explain energy flow - 30 minutes
6. EFD Guidelines with explanations - 15 minutes
7. Exercise with a product and EFD guidelines handout before disassembly - 30 minutes
8. Exercise with a product and EFD guidelines handout after disassembly - 15 minutes
9. Walkthrough of the exercise product with EFD guidelines - 20 minutes
10. Q&A - 15 minutes

In this lesson plan the first part is the lecture that gives the students a comprehensive overview of energy and its transformations. This is the most time consuming topic of the entire lecture. But the more understanding that the students have on this topic, the more effective they will be in implementing EFD. Some of the topics added from the initial list are the concept of system, subsystem, system boundaries, etc. The teachers still have the freedom to add or remove any of these topics. They also have the freedom to spend a different amount of time on each topic depending on the students' levels of understanding.

In this plan, the lecture includes the introduction of function structures and function trees as ways of modeling functionally. There is no need to go into detail on these topics. But it is good for the students to know that there are other techniques that can be used for functional modeling that the students can peruse on their own time if they are interested. Teachers should be careful in instilling the fact that the EFD is the ideal method for them with the right balance.

In this plan, two examples are included when the teacher is introducing the concept of energy flow. This ensures the students understand the concept of energy flow more firmly. It also includes a walkthrough of the EFD with the hand cranked flashlight after the students finish the actual EFD. This leads to the discussion with the students about the goals of functional modeling and how EFD achieves them. The differences can be studied and discussed. Teachers are recommended to encourage the students to conduct a quick brainstorming session and discussion about how they would solve the function differently. This discussion and walkthrough confirms the idea of functional modeling for decomposing the problem and abstracting the problem for innovation.

Again, the total time given here is a rough estimate. It would take about six class periods for the teachers to go through the comprehensive lesson plan. But generally the teachers can rearrange the lesson plan to meet their time limitations.

CHAPTER 6
CONCLUSION AND FUTURE WORK

6.1 CONCLUSION

The thesis started with the problem of the difficulties of teaching functional modeling technique in the *Engineer Your World* curriculum. Functional modeling is a valuable tool that can be introduced in high school curricula in order to show high school students the way engineers see, analyze and abstract a reverse engineering problem in order to generate innovative solutions. This gives them a peek into the world of engineering that may foster interest in engineering careers, which are in demand at the moment.

In order to solve the problem, a hypothesis was posed. An initial study was conducted in order to answer driving questions including:

Do the students think in terms of functions by default?

Do they need to think about components before functions?

In order to answer these initial research questions, clinical interviews were conducted. Four interviewees were selected and tasks that revealed their functional thinking were created. Clinical interviews were then conducted with them. It was found that the students think in terms of functions by default. Based on this, a strategy of simplifying function structures was pursued.

Some of the other findings from the interviews are that the students needed to be focused on functions and not jump to hypothesizing components. To address this, a set of guidelines for building the functional model was developed. During the interviews, in order to elicit functional thinking, the energy flow inside the product was used and the signal and material flows were ignored. This method turned out to be good for the students in terms of being simple and intuitive to use. This led to the development of the Energy Flow Diagram or EFD. The EFD is the new functional modeling tool that was developed for the *EYW* curriculum.

EFD is a simple flow diagram that takes into account the flow of energy inside the system. The energy needs to be transferred and transformed before the desired output can be achieved. This gives a key insight into functional thinking. Each of these energy transformations is actually a function performed by the device. This drastically reduced the complexity of the function structures while still enabling the decomposition of the problem as well as its abstraction, which are the main goals of functional modeling. The EFD was accompanied by a list of guidelines that the students should follow in order to develop the EFD.

The EFD was evaluated with the high school teachers. They were given the product, the guidelines, and an example of EFD through lectures and were asked to create the EFD for the given product. Multiple insights and confirmations of its usefulness were gained from the evaluation. The teachers validated this new way of functional modeling as very simple and intuitive to use. They liked the idea of using the guidelines to make them think in more detail. They asserted that this method would be a good standard for high school students. They also validated the hand cranked flashlight as a good product for all genders when learning the EFD.

The teachers gave feedback about the entire process that was implemented and the EFD was updated. One of the main suggestions concerned the guidelines. Some of the guidelines confused and added complexity to the process. One particular guideline was removed as a result of this finding. Some of the terminology used in the guidelines was not very familiar to them and they asserted that the students will not be familiar with some of the terminology either. This feedback led to the development of a lecture that teaches the principles of energy, energy amplification, energy storage, and mechanical advantage. This will help the students learn about these concepts and aid them in creating the EFD more effectively.

A lesson plan was then created factoring in all the feedback. This lesson plan was carefully constructed in order to fit the existing curriculum seamlessly. The aim was to transition the teaching of function structure to EFD without compromising time, quality or effort of the teachers. This plan is now recommended for the *EYW* curriculum as a replacement for the function structure.

6.1 FUTURE WORK

Though this research was conducted with a set goal and that goal was achieved, a number of possible paths are open for future work. Possible future developments were identified during the research period.

1. *Implement in high school*

The immediate next step in this research is the implementation of the EFD presented in this thesis directly to high school students. In this thesis, the EFD was validated through high school teachers, who will be the ones instructing students. The teachers fulfilled the criteria of the EFD to be implemented in high schools. But the classroom problems that arise out of actual implementation are yet unknown. Moreover, the lesson plan was designed based on feedback on the tool alone. Feedback on the lesson plan itself was not solicited from the teachers. This is another study that can be conducted.

The most common problems that teachers may encounter in the classroom are:

1. Lack of time
2. Lack of resources
3. Lack of interest in the product used

In a classroom setting, there will be factors that are beyond the teacher's control, and there is only a certain amount of control that can be exerted. The problems listed above can only be solved when the EFD is implemented directly in the high school and observations are made. These observations can serve to reveal valuable insights on the possible reasons behind the problems mentioned above. They may even shed some light on how to tackle those problems.

Though 90 minutes seems reasonable to implement the EFD module, the students' understanding and questions and clarifications might take more time, which is something that can only be found through actual implementation in high school. Some schools may lack the resources to buy more of the recommended products for the students to disassemble. Some of the products do not work the same way once the product is disassembled. So buying the products again and again for the students to disassemble becomes expensive.

2. *Guidelines for material and signal flow*

The EFD completely ignores the flow of material and signal. This is its biggest disadvantage. This decision was made in order to gain intuitiveness and simplicity. But this research could be extended by including the material and signal flow. This may be done by developing separate guidelines for materials and signals. These guidelines for the signal and material flows may then be incorporated with the energy flow in a multistage manner where the entire functional model is created in three stages: the first stage of capturing energy flow, the second stage of capturing material flows and the third stage of capturing signal flows.

A multistage process of the functional modeling may allow the students to learn the actual function structure in a simpler way while maintaining the intuitiveness of the function structure. The simplicity could be achieved by teaching the entire model through a multistage guideline. This way of teaching may take time, but it breaks down the process step by step, making it much simpler to use. This way of solving the problem could be a pedagogical research topic that would not change the technique much. And this may incorporate the black box into the curriculum again. This would give the students the entire range of possibilities of innovation that was compromised in the EFD.

3. *Increase sample size*

The sample size of the initial study was 4 and the sample size of the implementation was 16. For the initial study, 4 is a good number because the initial study was in the form of clinical interviews. It was more important to focus on the questions and capture the students' ways of learning. But in the implementation, 16 might be a low number. Though the sample was a good one with teachers from all over the country and teaching different science subjects, the sample could still be larger to give a more accurate picture of how easy and intuitive the teachers found the EFD to be. A separate study that brings together more teachers could be undertaken.

4. *Add a concept generation tool*

One of the drawbacks while testing this tool was that the level of innovation the tool brought to the problem was not very high. Though the lecture was designed to show the students the idea of abstraction and how abstraction helps in thinking of other ways to solve the problem, the actual increase in innovative solutions was not measured. This could be done in the future by studying the solutions that the students generate during the brainstorming of concepts after abstracting the problem through EFD. They need to compare these solutions generated with concepts generated after abstraction using function trees or function structures. This comparison will reveal the increase or decrease in innovation.

Another way to do this is to create a concept generation tool that is easy to teach in about 20 minutes and implement it right after the EFD is taught. This saves a lot of time while waiting for the curriculum to reach the concept generation phase and it might be difficult to see if the innovation happened as a result of the EFD. This new 'innovation' testing tool can be implemented as soon as the EFD is taught as a measure of innovation.

5. *Find a completely new way of functional modeling*

The idea for EFD came from the initial study and the response of the interviewees when they were introduced to energy flow. This was recognized as a way to teach functional modeling through the energy flow alone. It is possible, however, that there might be a completely new way of functional modeling that can be developed if the research does not follow the same path.

6. *Impact of socio-economic status that affects the learning of EFD - better product, better grasp*

One key idea included at the end of the lesson plan is that students can be allowed to choose and work on their own product. This would give them a better grasp of the functional modeling technique. The main drawback of this is the cost associated with disassembly of the products. Sometimes the products, once disassembled, will be very hard to put back together. In such a scenario, the school would have to purchase replacements for the unfixable ones. But the entire *EYW* program was designed to make engineering education accessible and an important criteria for that to happen is to keep the cost low.

A socio-economic study needs to be undertaken on the school, the regions and the backgrounds of the families in terms of the money they will be able to spend on a course like this. This information could be used to inform decisions on how many products per course would be affordable, what type of products could be used that are inexpensive as well as effective, etc. It may be possible to identify other products as options for the students can work on. This does not have to be part of the curriculum.

APPENDIX I
BLACK BOX MODEL PROCEDURE

In the context of reverse engineering and new product development, a black box is a tool that is used to understand and record the inputs and outputs of a product in terms of energy, material and signal flows. A simple representation of the black box is shown in the figure below.

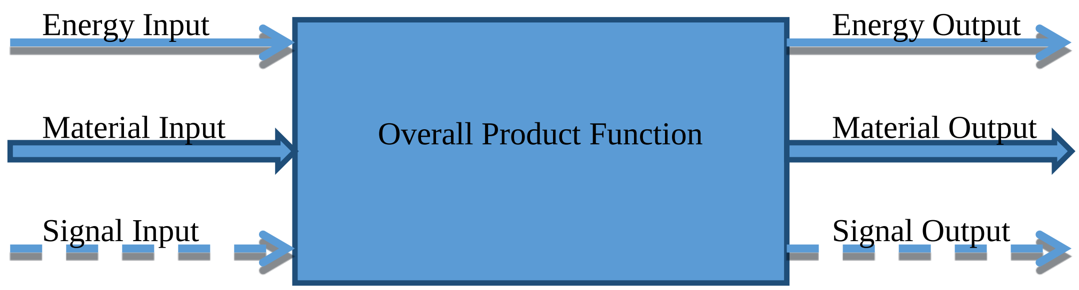


Figure 12: Black box model (Otto & Wood, 2001, p 162)

1. The product overall function is recorded inside the 'black box'.
2. Different arrow types indicate different types of flows in the system. The types of flows are energy, material and signal.
3. An energy input is manipulated in order to achieve the product function. An energy output generally results from one or more transformations of input energies. Examples of energies are human energy, electrical energy, hydraulic energy, mechanical energy, and thermal energy.
4. A material input is matter that enters the system. Examples include human hand, coffee beans, cold air, and water. A material output is provided by system after completion of the product function.
5. A signal input is information needed for the product to function. Examples include ON/OFF, power setting, and speed setting.

APPENDIX II

ACTIVITY DIAGRAM EXAMPLE

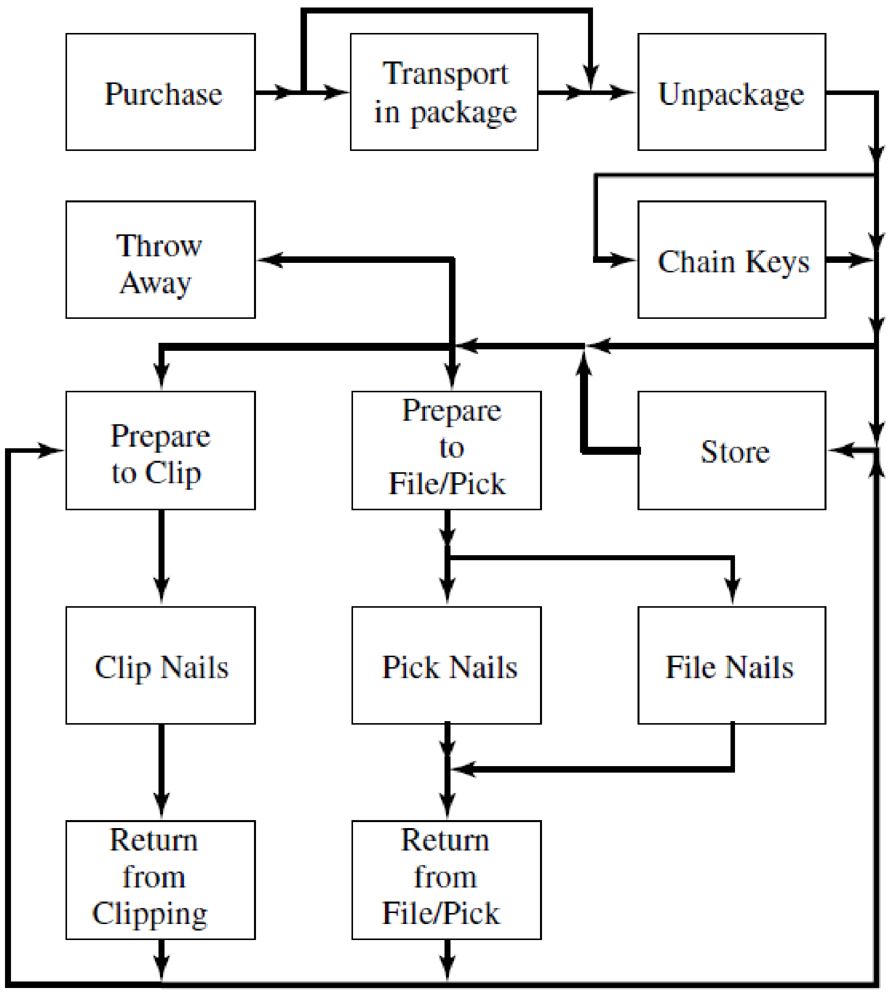


Figure 13: Activity diagram for nail clipper (Otto & Wood, 2001, p. 168).

Figure 13 is an example of an activity diagram for a common fingernail clipper. Notice that all the choices of language for the diagram reflect the user's perspective of interaction with and operation of the product from the initial purchase to the final disposal.

APPENDIX III

SAMPLE FUNCTION STRUCTURE

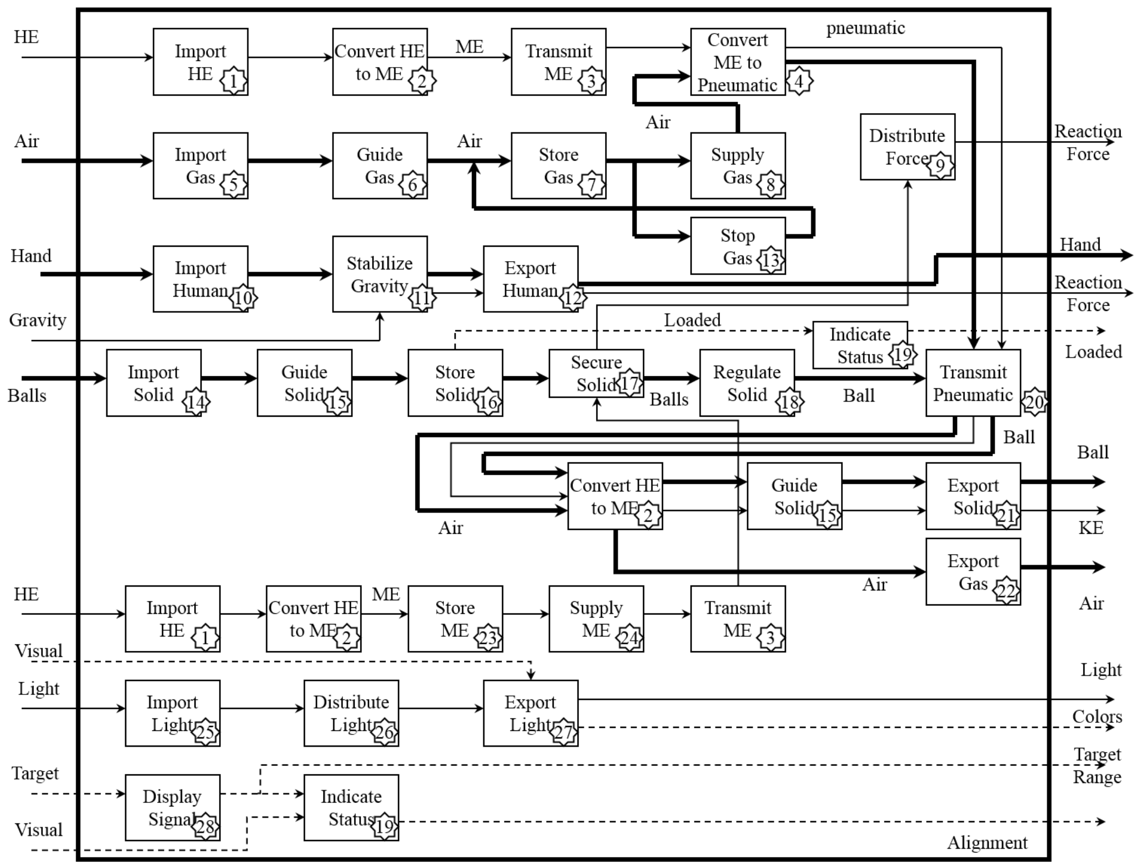


Figure 14: Function structure for Nerfball Blaster (Crawford, 2012)

Figure 14 shows an example of a complete function structure of a Nerfball Blaster. The functions are in verb-object form and are completely abstracted and component independent. The diagram provides a good example of material, energy and signal flows.

APPENDIX IV

EFD FOR HAND CRANKED FLASHLIGHT

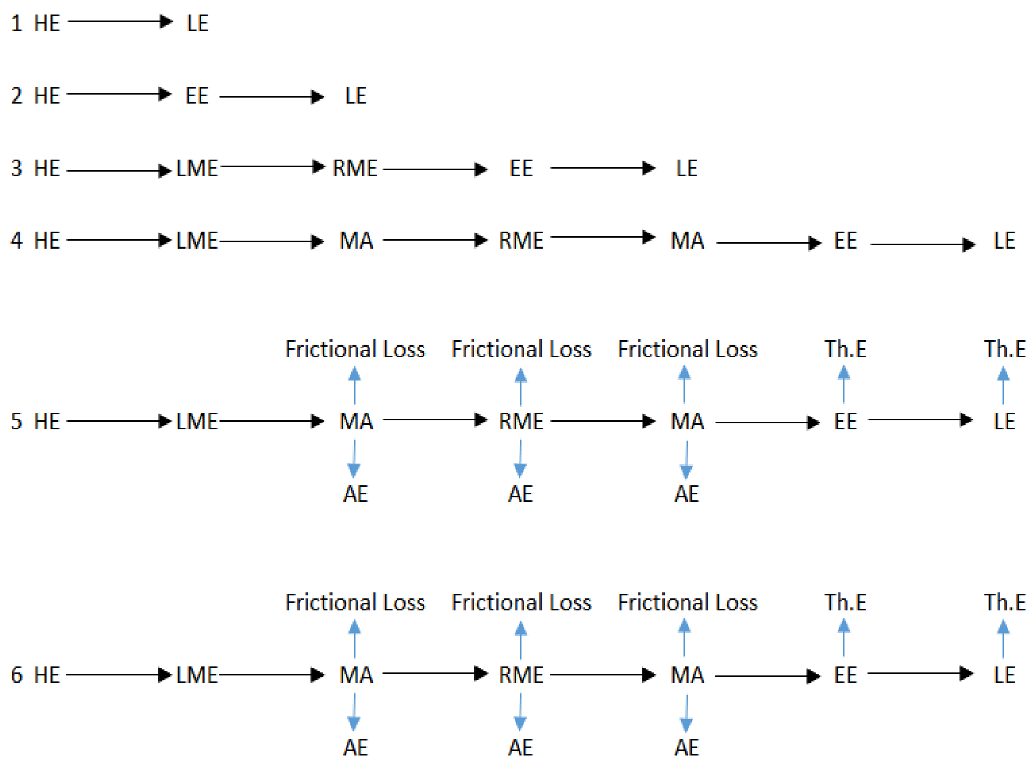


Figure 15: EFD for hand cranked flash light

The EFD for the hand cranked flashlight here was developed based on the EFD guidelines presented in Chapter 4. The example starts with the simple input and output energies and expands at each step to include the energy transformation that happens between two functions. The table below shows the step by step creation of the EFD for the hand cranked flashlight.

Guidelines	Energy Flow Diagram Rationale
1. Start with input and output energy	The input of human energy through manual cranking and the output of light energy were identified.
2. Identify the main energy conversions/transformations between input and output	The light bulb needs electricity to work. So the human energy must first be converted into electrical energy before it can power the light bulb.
3. Identify the intermediate energy conversions. Make assumptions when necessary.	Based on the fluctuating intensity of light, an assumption that a generator is used inside was made. For that to operate, there needs to be a rotational energy input. And the rotational energy can be achieved by converting the human energy to linear mechanical energy (the crank is pushed in a linear manner) and then to rotational mechanical energy.
4. Can the system benefit from having a mechanical advantage, energy storage, energy amplification*? Identify and include them	The system can benefit from having a mechanical advantage at the rotational energy by increasing the speed of rotation and at the linear mechanical energy to reduce the human effort. Hence, they were added.
5. Identify the energy losses	The losses here are in the form of heat energy and acoustic energy. And they occur at almost every step of the energy transformation. Frictional loss is recorded separately because the heat and acoustic energy loss from friction cannot be separated. Note: The heat and frictional losses can be ignored in the EFD because they are inevitable. The acoustic loss on the other hand was included because it can be minimized.
6. Does the energy flow follow the laws of conservation of energy? If not, go back to step one and verify the energy conversions	The flow was checked for any discount of energy transformation and if all the input and out energy flows were accounted for.

Table 4: Rationale behind EFD for hand cranked flash light

LEGEND

Abbreviation	*Expansion*
HE	Human Energy
LME	Linear Mechanical Energy
MA	Mechanical Advantage
RME	Rotational Mechanical Energy
EE	Electrical Energy
LE	Light Energy
AE	Acoustic Energy
Th.E	Thermal energy

APPENDIX V

INITIAL STUDY MATERIALS

Post Questionnaire

(15 minutes)

Questionnaire:

1. Use a number on a scale of 1 to 5 to answer the following questions

   I. On a scale of 1 to 5, with 1 being least helpful and 5 being most helpful, how helpful were the energy flow guidelines to consider new energy conversions that you did not think of before?

   II. On a scale of 1 to 5, with 1 being no difference and 5 being very different, how different was the flow diagram compared to the one done without guidelines?

   III. On a scale of 1 to 5, with 1 being very difficult and 5 being very easy, how difficult was it to understand these guidelines?

   IV. On a scale of 1 to 5, with 1 being very difficult and 5 being very easy, how difficult was it to implement these guidelines?

   V. On a scale of 1 to 5, with 1 being least useful and 5 being most useful, how useful was the energy/component table in understanding the functions of the device better?

2. Any specific feedback for the energy flow guidelines?

3. Feedback on the product used? Was it easy or hard? Interesting or boring?

4. What was the most interesting thing about the flashlight's energy conversions that was most fascinating to you?

5. How do you think this technique will work in high school?

APPENDIX VI

FINAL PRE/POST-TEST

Answer the following questions to the best of your ability:

1. List all the energy inputs and all the energy outputs for the following devices (20)

I. Flashlight

Energy Inputs

Energy Outputs

II. Vacuum cleaner

Energy Inputs

Energy Outputs

2. Can you name the intermediate energy transformation that happens in these devices? (10)

I. Flashlight

Energy Inputs	Intermediate energy transformation	Energy Outputs

II. Vacuum cleaner

Energy Inputs	Intermediate energy transformation	Energy Outputs

3. List at least 2 energy losses for the devices below (8)

I. Flashlight

	Type Of Energy Loss
1	
2	
3	
4	

II. Vacuum Cleaner

	Type Of Energy Loss
1	
2	
3	
4	

4. List 3 products that go through the following energy transformations (9)

Electrical energy → Rotational energy → Kinetic energy

I.

II.

III.

5. List 3 components that is used for this energy transformation inside a device (9)

Rotational Energy → Linear Energy

I.

II.

III.

6. Create your own energy flow diagram for the hand cranked flashlight given, completely capturing all the energy inputs, outputs, transformations and losses. (30)

Name:

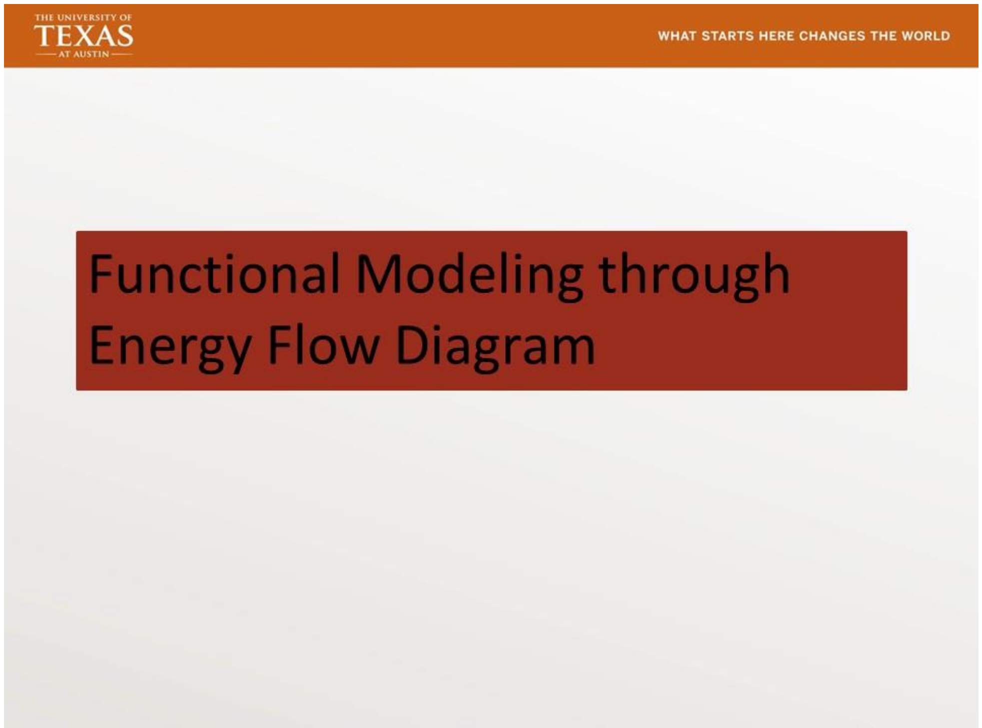
Gender: Male / Female / Other (Circle one)

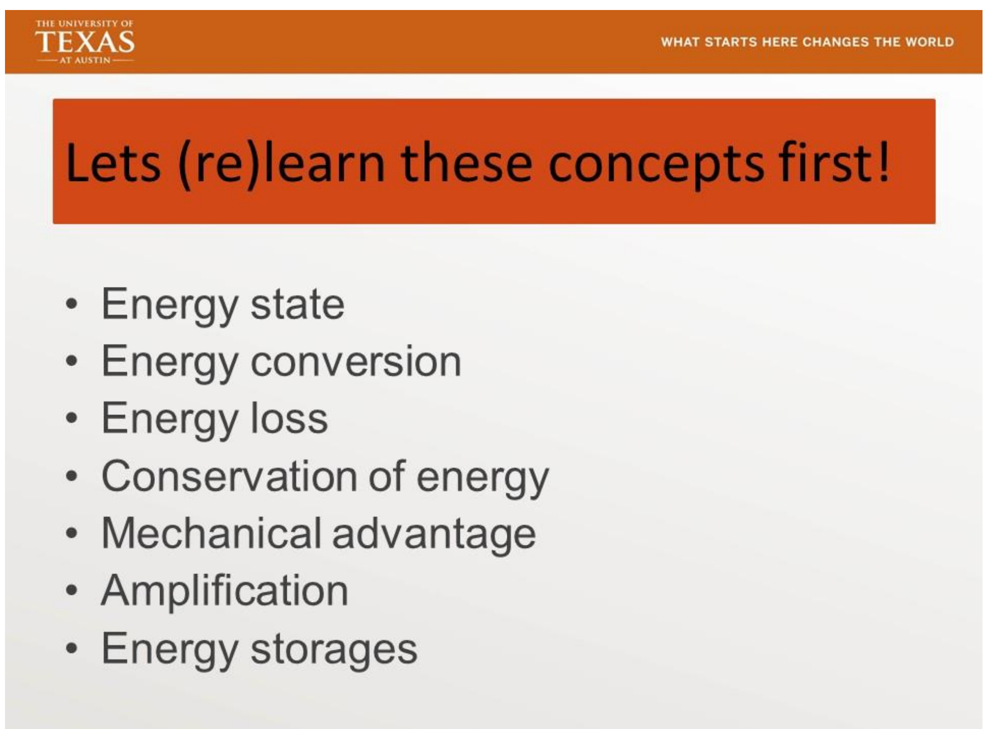
Major and Year:

Use for study: Yes / No (Circle one)

APPENDIX VII

SUGGESTED LECTURE





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WHAT STARTS HERE CHANGES THE WORLD

Energy State

The capacity of a body or system to do work. It exists in one form or another.

E.g. of different forms of energy energies

- Kinetic energy
- Potential energy
- Electrical energy
- Mechanical energy
- Heat energy (Thermal)
- Chemical energy
- Human energy (This is form of mechanical energy that we are categorizing separately for the purpose of product usage)
- Magnetic energy
- Nuclear energy

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WHAT STARTS HERE CHANGES THE WORLD

Energy conversion

It is the process of converting one form of energy to another form. It is also called as transformation of energy. There is always energy loss when conversion takes place.

E.g. of transformation of energy

- Potential to Kinetic - When a rubber band is stretched and zinged from your finger
- Electrical to Mechanical - Motor
- Mechanical to Electrical - Generator
- Chemical to Electrical - Battery
- Human to Electrical - Human cranking to charge a battery (hand crank radio). Human - Mechanical - Electrical
- Mechanical to heat energy - Friction

Energy loss

It is the energy that is lost when converting one form of energy to another. By loss, it means they are converted to energies that we are not tapping or cannot be tapped.

E.g of energy loss

- Energy lost due to heat and noise when gears are meshing. We are only concerned about the mechanical energy.
- Energy lost in form of heat when a light bulb is burning. We are only concerned about light.

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WHAT STARTS HERE CHANGES THE WORLD

Law of conservation of energy

The total amount of energy in a system remains constant. Energy can neither be created nor destroyed but it can be transferred from one form to another.

Input Energy = Output Energy + Losses

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WHAT STARTS HERE CHANGES THE WORLD

Mechanical Advantage

- It is a measure of force amplification achieved by a mechanical system.

E.g. Lever system

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WHAT STARTS HERE CHANGES THE WORLD

Energy Amplification

Increasing the energy level by a factor. Note that energy cannot be created. It had to come from a different source.

E.g. of energy amplification systems

- Megaphones

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WHAT STARTS HERE CHANGES THE WORLD

Storage of Energy

It requires a physical medium. Storing energy for later use. There's always loss of energy when trying to use that energy.

E.g. of energy storage

- A stone balancing on a cliff - Stores potential energy due to gravity
- Compressed spring - Stores potential energy
- Battery - Stores electrical energy (Note this also converts chemical energy to electrical energy. The storage is in form of chemicals, but the energy tapped is in form of electrical energy)
- Gasoline - Stores thermal energy (Same explanation)

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WHAT STARTS HERE CHANGES THE WORLD

Functional Modeling

- Tools design engineers use to abstract their product/problem
- Energy flow diagram is one such method to abstract the product/problem

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WHAT STARTS HERE CHANGES THE WORLD

Energy flow diagram

- It's a diagram depicting the flow of energy in a system.
- This flow can go through multiple transformations, amplifications and storage phases before it is converted to the desired energy output.
- As with any energy transformation, energy loss occurs at every stage and has to be captured.

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WHAT STARTS HERE CHANGES THE WORLD

Lets start with an example

Hair dryer


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WHAT STARTS HERE CHANGES THE WORLD
What is the input to this device?
Electrical Energy


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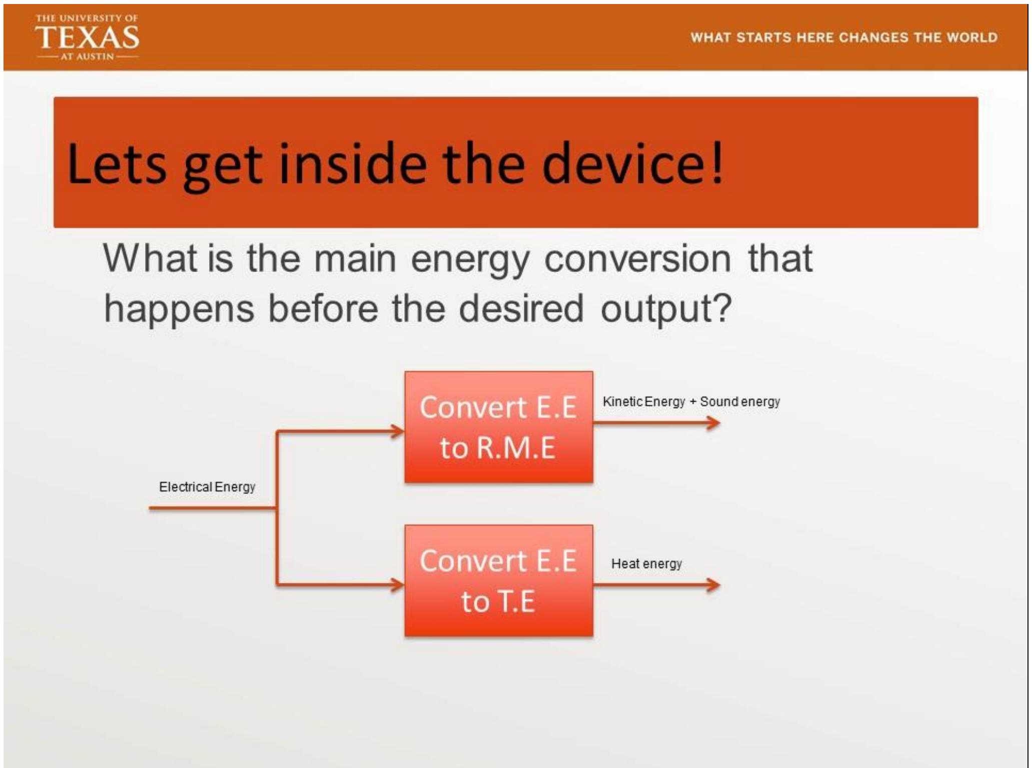
WHAT STARTS HERE CHANGES THE WORLD
What is the output to this device?
Electrical Energy
Heat energy + Kinetic Energy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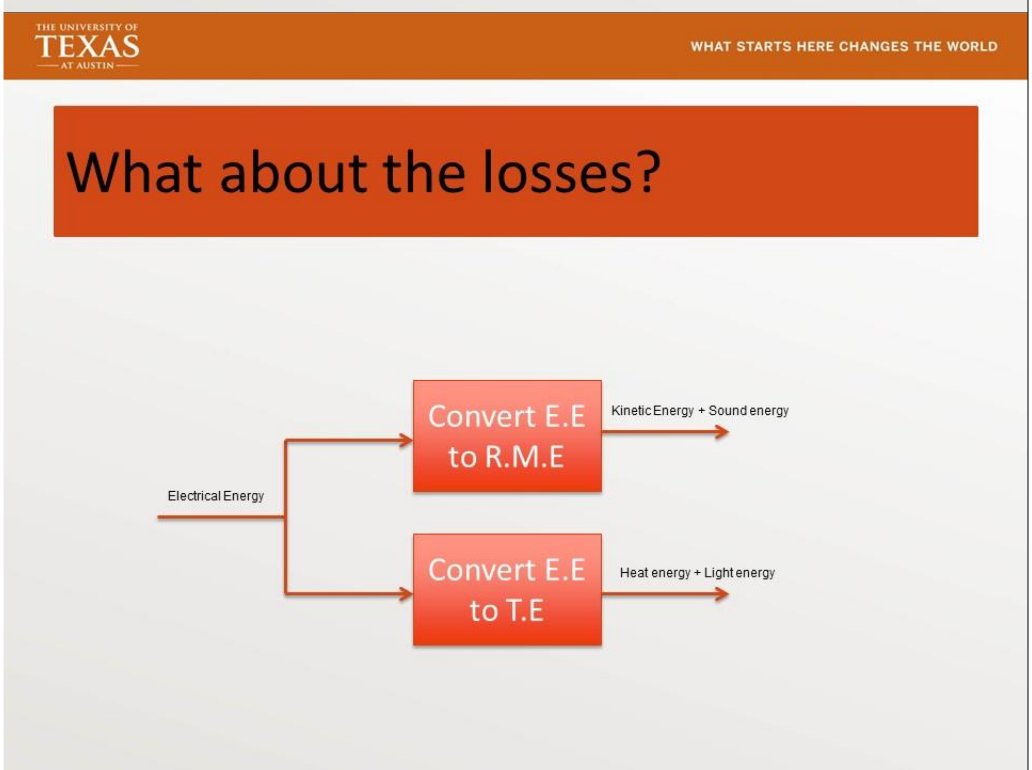
WHAT STARTS HERE CHANGES THE WORLD
Lets get inside the device!
What is the main energy conversion that happens before the desired output?
Electrical Energy
Convert E.E to R.M.E
Kinetic Energy + Sound energy
Convert E.E to T.E
Heat energy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WHAT STARTS HERE CHANGES THE WORLD
What about the losses?
Electrical Energy
Convert E.E to R.M.E
Kinetic Energy + Sound energy
Convert E.E to T.E
Heat energy + Light energy

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Lets add the output!

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Energy flow diagram guidelines

In order to create an energy flow diagram for any product, the following guidelines must be followed when creating one.

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Energy flow diagram guidelines (Refer to handout)

1. Start with input and output energy
2. Identify the main energy conversions/transformations between input and output
3. Identify the intermediate energy conversions - Make assumptions when necessary
4. Can the system benefit from having a mechanical advantage, energy storage, energy amplification? Identify and include them
5. Identify the energy losses
6. Does the energy flow follow the laws of conservation of energy? If not, go back to step one and verify the energy conversions

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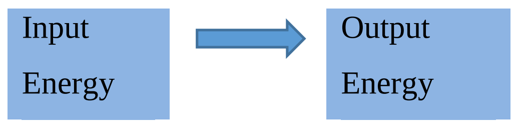
Exercise – Create an energy flow diagram for the product given

APPENDIX VIII

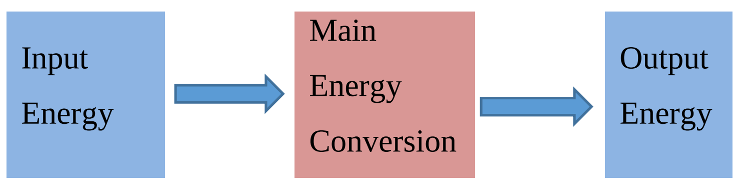
EFD GUIDELINES HANDOUT

Energy Flow Diagram Guidelines:

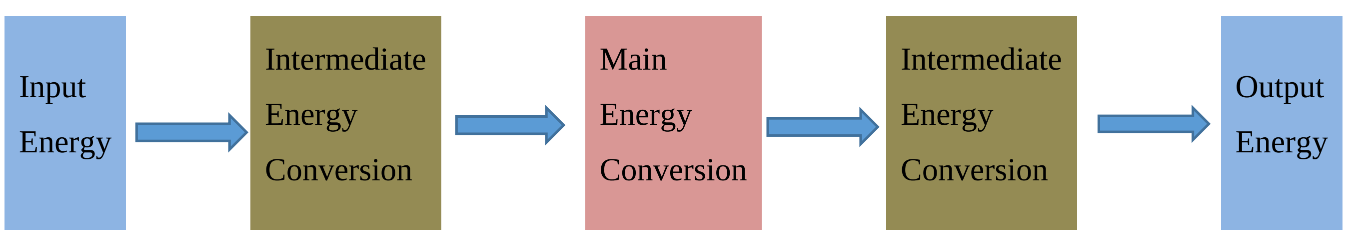
2. Start with input and output energy from the black box



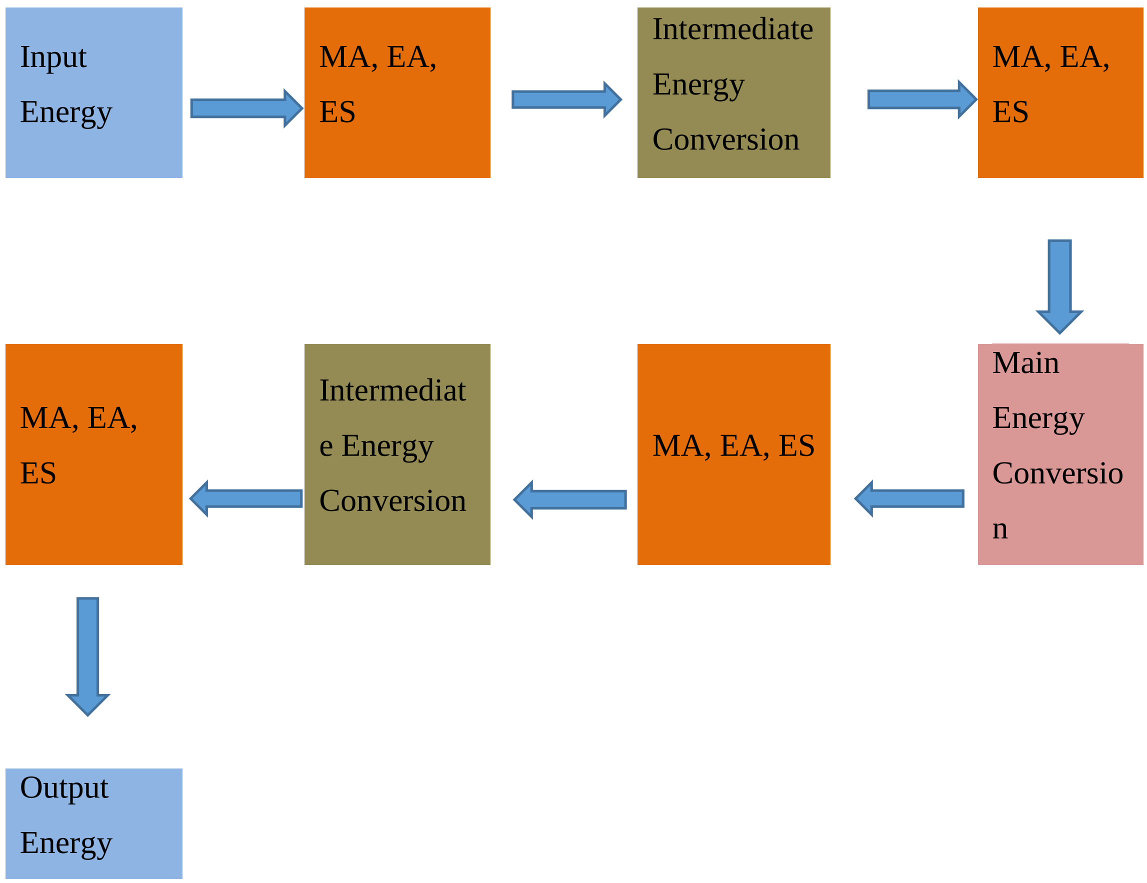
3. Identify the main energy conversions/transformations between input and output



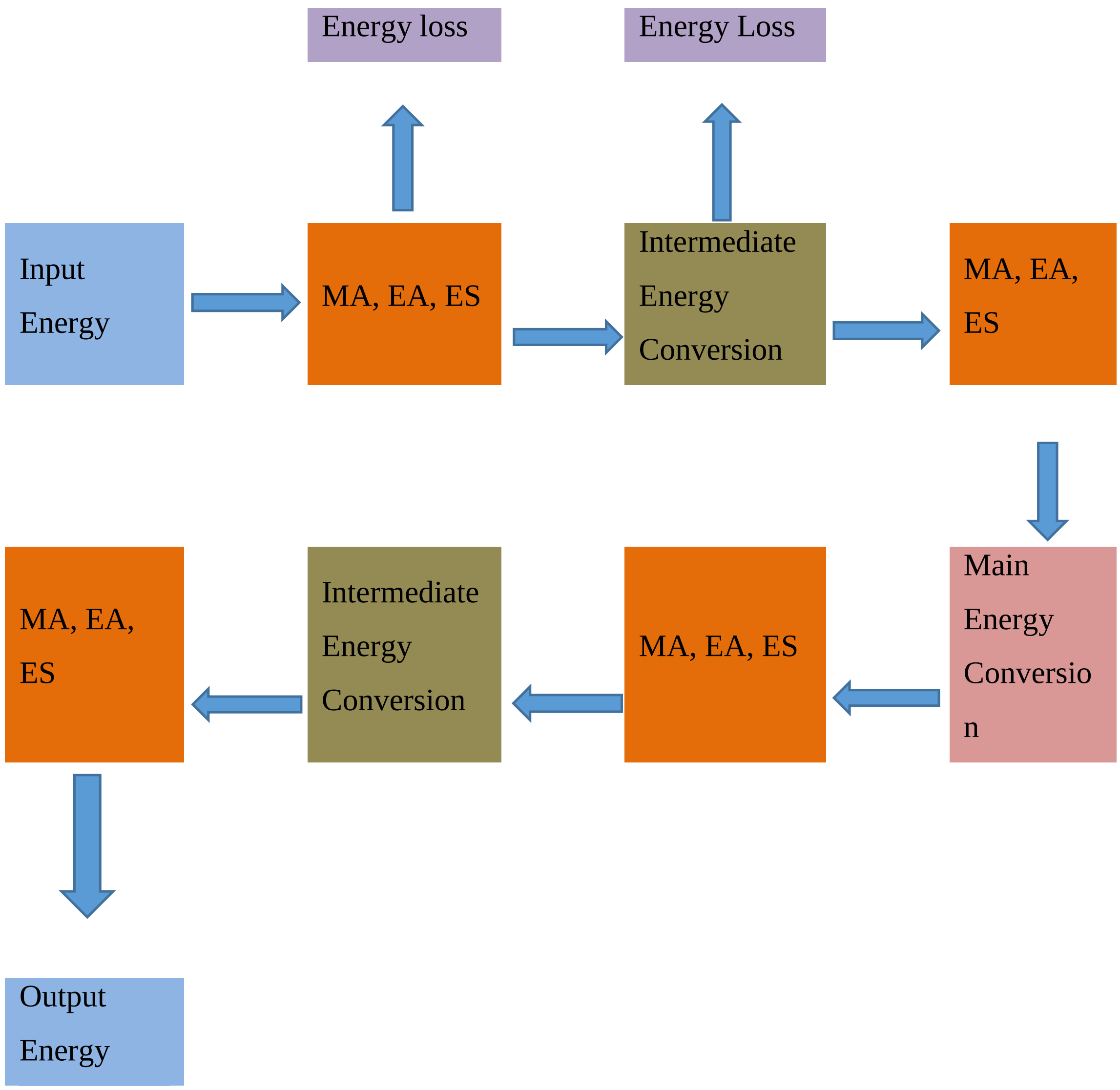
4. Identify the intermediate energy conversions - Make assumptions when necessary.



5. Can the system benefit from having a mechanical advantage, energy storage, energy amplification? Identify and include them



6. Identify the energy losses



7. Does the energy flow follow the laws of conservation of energy? If not, go back to step one and verify the energy conversions

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